Effects of Fire on Air

A State-of-Knowledge Review
National Fire Effects Workshop
Denver, Colorado
April 10-14, 1978

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EFFECTS OF FIRE ON AIR[1]

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Prepared for the Forest Service National Fire Effects Workshop
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D. V. Sandberg
Research Forester, Seattle, Wash.

J. M. Pierovich
Program Manager, Macon, Ga.

D. G. Fox
Project Leader, Ft. Collins, Colo.

E. W. Ross
Assistant Director, Delaware, Ohio

Forest Service, U.S. Department of Agriculture

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[1] The Air Quality Work Group was established to prepare this state-of-knowledge report; the group members included the authors and A. T. Altobellis, J. L. Hickman, L.O. Bancroft, and R. W. Mutch, who reviewed the report and collaborated in setting research priorities.

PREFACE

Recent changes in Forest Service Fire Management Policy make it clear that resource managers today need a great deal more information on the physical, biological, and ecological effects of fire. They will need information on fire behavior and fire effects as a basis for analyzing the benefits, damages, and values of various fire management alternatives. Managers must be able to place a value on all resources if they are going to incorporate fire and its effects into land management plans. The Forest Service is committed to the concept that fire management planning has to be a fundamental part of all our planning.

Recent laws and regulations also give additional guidance for the Forest Service to use in developing land management plans for each unit of the National Forest System. These plans must coordinate outdoor recreation, range, timber, watershed, wildlife and fish, and wilderness resources. Interdisciplinary planning is vital, and research must cover the same universe as our planning; therefore, interdisciplinary research is a must.

The effects of fire have been studied since the beginning of organized Forest Service research, but the results are scattered over a wide range of outlets. In addition, research is conducted on the effects of fire under several appropriation line items, and in some instances lacks the interdisciplinary approach needed to make the results as useful as possible to land managers.

The National Fire Effects Workshop was held April 10 through 14, 1978, as a first step in responding to the most recent changes in policies, laws, regulations, and initiatives. One of the major Workshop objectives was to prepare a report indicating the current state-of-knowledge about the effects of fire on various resources. These reports formed the basis for pinpointing knowledge gaps. Using this information and input from land managers, priorities for research needed on the effects of fire were established.

Six work groups were established to prepare the state-of-knowledge reports on the following subjects: soil, water, air, flora, fauna, and fuels. Work group members were mainly Forest Service research scientists, but individuals from the National Forest System, Bureau of Land Management, National Park Service, Fish and Wildlife Service, and Bureau of Indian Affairs also participated.

We hope these state-of-knowledge reports will prove useful to researchers and research planners, as well as to land and fire management planners. Each report will be published as an individual document. A separate bibliography will also be included in this series in an effort to provide a source document for most of the literature dealing with the effects of fire.

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INTRODUCTION

Objective

The objective of this report is to summarize the current state-of-knowledge of the effects of forest burning on the air resource, and to define research questions of high priority for the management of smoke from prescribed and wild fires. Our purpose was to provide background for discussions at the Forest Service Fire Effects Research Workshop held in Denver, April 10-14, 1978.

The scope of this review is limited to those topics that affect setting research priorities. Application of the best available knowledge for managing smoke from wildland fires requires more information than is presented here. The authors acknowledge that other state-of-knowledge publications are in progress that will include additional detail on some aspects of this complex subject and reflect other points of view.

Knowledge of the effects of fire on air quality is applied differently by three basic user groups: (1) environmental agencies, (2) fire management, and (3) land use planners. In the section on Research Applications, we describe the operation of each user group, and identify the improvements needed in their operations. Current knowledge that is common to all user groups is reviewed separately in the section on Research Review, according to the research discipline involved. Research needs are summarized in the Summary and Conclusions section.

Problem Statement

Forest and rangeland environs are both a significant source and receptor of air pollutants. Land managers have legal, moral, and professional responsibilities to prevent and control air pollution, as well as to protect wildland values from its damaging effects. The quality of wildland management is dependent on the acquisition and systematic use of knowledge gained through research.

Use of prescribed fire is constrained by smoke management, and the number of areas constrained will increase dramatically in the next decade. Unless wildland smoke management systems are provided a better technological base, land management objectives that can most effectively (and often, only) be met with managed fire will not be realized.

Important new air quality legislation is being interpreted and applied. Strong justification for using the atmosphere is required of the many competing users. The quality of the job done in air resource management will reflect our levels of knowledge in both the ecological and economic relationships between wildland management and air pollution. Current knowledge is considerable, but remains inadequate.

Prior Reviews

Extensive reviews are currently available in the literature and others are expected to be published in the next year. Komarek (1970) provides an example of reviews from an ecological point of view. With 107 references, he characterizes the smoke from prescribed fires as natural, local, and innocuous. Others have provided reviews more directly from an air quality perspective. Hall (1972) summarized the thermal and chemical processes involved, and again concluded that the adverse effects of prescribed burning are limited to local visibility reduction. He suggested that these are far more than compensated for by the reduction in wildfire hazard. He characterized emissions as being made up of the pyrolysis and distillation products and various combinations of their components in all degrees of oxidation. Hall also observed that "these complex processes, the amounts of substances burned, escaping unchanged, or altered by heat and intermolecular reactions, or by partial oxidation, present infinite possibilities in the matter of final products."

Hall concluded that much additional research is needed, and stated:

> There are many gaps in our knowledge. In the first place, we do not know the true nature and amounts of the material burned. Clearly, part is wood, but we burn foliage, twigs, old and young bark, brush and grass in the understory. Data are plentiful on products of combustion of wood and so-called backyard trash, of unknown composition and uncontrolled conditions of burning.
>
> Tables of emission factors and emission inventories are of little help with regard to forest fuels because they are made up of guesses at volumes, nature and conditions of burning of fuels and interpretations of results. We need a great deal of carefully controlled work in order to have definitive answers to the questions:
>
> 1. What do we burn?
> 2. Under what conditions should we burn?
> 3. What are the products under variable conditions with specific classes of fuels?

Cramer (1974) reinforced that conclusion by listing 14 prominent forest fuels with substantially different chemical characteristics. His review of the air quality influences of forest residues restated Hall's conclusions, emphasized the opportunity to manage smoke by scheduling, and stressed the need for an "environmentally balanced decisionmaking process (based on) the risk of destructive fire, deterioration of forest production, and consideration of other resource, environmental, and economic values." Cramer added:

> Many aspects of the presence of forest fuel smoke in the atmosphere are unknown and offer opportunities for research. A general need is for development of a decision matrix permitting selection of residue treatment method on the basis of effects on the complete environment over the short and long term. Treatments would include but would not be restricted to various forms of burning. Effects would include the impact of managed smoke. Considerable additional knowledge is needed to fill all the blanks in such a matrix. Some of the questions that need answers follow.
>
> 1. Specifically, how effective are precipitating cloud systems in removing particulate and gas components of forest smokes?
> 2. What are the important components in forest smokes from the major kinds of fuels in both flaming and glowing combustion; what processes are these components involved in under various atmospheric conditions and in mixture with other substances commonly found in the air; and what are their removal mechanisms?
> 3. What are the actual toxicological properties of smokes from the various forest fuels?
> 4. How can the field forester readily estimate the convective column strength he can generate from a given combination of (a) fuel composition, loading, and arrangement; (b) fuel moisture condition; (c) size of area aflame; (d) wind profile; and (e) atmospheric stability?
> 5. What amounts of what atmospheric gases are taken up and released by various microbiota in the forest floor under diverse forest situations?
> 6. Can an index be developed based on weather factors and assuming constant emission of all usual sources that will indicate the level of air quality to be expected in a particular locality for given season and weather conditions? (Necessary for judging effect of intermittent nonpoint sources like forestry burning.)
> 7. What methods can be developed for predicting in more detail the diurnal patterns of stability and wind profile over wide areas of mountainous terrain for application to individual fire and smoke dispersion problems?
> 8. What are the details of some of the typical important weather situations that permit good smoke dispersion and of those that create smoke dispersion problems?

9. What is the normal balance of emissions to and uptake from the atmosphere of hydrocarbons, CO and CO_2, and nitrogen compounds in various typical forest situations?
10. What smoke dispersion coordination aids can be developed that will monitor and project plume locations and smoke densities in several strata and in air stagnation areas at the surface for routine use in scheduling burns?

The Southern Forest Fire Laboratory Staff (1976) authored a guidebook for southern forestry smoke management that reviews current knowledge, and introduces a system for predicting and modifying smoke concentrations. Currently, the *Guidebook* is the best published reference for source assessment, and it will be quoted extensively here. A parallel sourcebook has been identified as being needed to provide much additional information to specialists (Mobley 1976).

The Environmental Protection Agency (EPA) has contracted with Monsanto Research Corporation to revise a draft of a document, "Source Assessment: Prescribed Burning, State-of-the-Art," that will be a comprehensive summary of source description, emissions character and amount, impact assessment, and control technology. EPA source documents are written to aid State and regional agencies in setting goals and control strategies.

The EPA Region X contracted with GEOMET, Inc., to characterize burning practices, and the impact of emissions in Washington and Oregon (Cook et al. 1978). The report concluded that:

> Procedures exist for minimizing uncontrollable fire hazards and air quality impacts of prescribed forestry burning, but because of inadequate knowledge of emissions and the lack of data about the interrelations between fires, local meteorology, and local topography, the accurate prediction of air quality impacts is generally not possible.

A research objective recommended in the report is the "capability for prediction of air quality impacts of fires through use of operation-oriented source strength and dispersion models." Included in the suggested research are:

1. An emissions source strength model to predict heat release and emissions rates, based on knowledge of fire behavior, fuel type, and burning technique.
2. A dispersion model for complex terrain and long-range transport, including prediction of secondary pollutant formation.
3. Derivation of appropriate emission factors for forest burning.
4. A program to quantify and improve techniques of air quality monitoring and the impact of forestry burning.
5. Health effects studies to evaluate the potential impact of CO, NO_2, respirable particulate matter, halogenated vapors, and oxidants.
6. Economic tradeoff analyses to weigh the costs and benefits of prescribed fire against alternatives to burning.

These expressions of research need are included here for review. Many will be repeated in our analysis of research priorities.

The Clean Air Act

The Clean Air Act of 1963 (PL 88-206), as amended,[2] is the primary legislative tool for improving and maintaining air quality in the United States. Many requirements of the Act, and related Federal regulations, apply to Forest Service management activities. Summaries of the Act, its amendments, and their implications to forestry current to 1978 are available (Paulson et al. 1978, McCleese et al. 1976; Searcy 1976).

The 1970 amendments to the Act required the Administrator of the Environmental Protection Agency to identify air pollutants that have adverse effects on public health and welfare, and to establish primary and secondary National Ambient Air Quality Standards for each pollutant identified. Each State was required to develop an implementation plan (SIP) for maintaining air quality within these national standards.

The air space of the United States is divided into Air Quality Control Regions (AQCR) for the purposes of planning, administering, and controlling air pollution. These regions, like watersheds, encompass areas of similar characteristics and influences. For those regions where any National

[2]Significant amendments to the Clean Air Act include the following: The Clean Air Act Amendments of 1966—PL 89-675 (10/15/66), The Air Quality Act of 1967—PL 90-148 (11/21/67), The Clean Air Amendments of 1970—PL 91-604 (12/31/70), Clean Air Act Amendments of 1977—PL 95-95 (8/7/77).

Ambient Air Quality Standard is exceeded, or any standard is expected to be exceeded in the next 10 years, the States were required to implement a plan for bringing air quality within the standards in a specified period of time. As might be expected, the primary emphasis of EPA and the States has been on reducing pollution from major sources such as heavy industry, coal-fired power plants, and motor vehicles. A major effort was made to reduce pollution significantly from these sources by 1975.

As progress was made in cleaning up the air over industrial and urban areas, public attention began to shift to other areas. In 1972, a Sierra Club suit led to a court order requiring the Administrator of EPA to disapprove all SIP's not containing provisions for preventing significant deterioration in any portion of any State where air quality was superior to national standards. The protection of esthetic, scenic, and recreational values in rural areas was of particular concern. In response to this suit, in December 1974, EPA issued regulations setting up a mechanism for preventing significant deterioration (PSD) of air quality in areas where air pollution levels are currently below the national standards.

Further, the court made it clear that the Clean Air Act required the development of a plan, including provisions for continuing attainment and maintenance of the ambient standards well beyond the attainment date. EPA developed procedures for each State to use in addressing the maintenance issue. Each State was asked to review the air quality within its jurisdiction and identify those areas (usually counties) that, due to anticipated growth, had the potential to violate ambient standards during the next 10-year period. These areas were identified as Air Quality Maintenance Areas (AQMA). Designation of AQMA's was completed in 1975. The States are now assessing strategies that will rectify nonattainment and provide continuous maintenance of ambient standards. Revisions of SIP's for this purpose will be completed in 1979, in accordance with the Clean Air Act Amendments of 1977.

The EPA program to prevent significant deterioration of air quality went into effect in December 1974. The 1977 amendments require all areas of the country to be placed in three broad classifications. Class I includes all areas where essentially any degradation of air quality would be considered significant deterioration. About 30 million acres of land in 37 States has now been designated Class I. Virtually all Federal Wilderness and National Park lands are Class I. Currently all other forest and rangelands are classified as Class II, and there are no lands under the Class III designation. Moderate degradation over baseline concentrations for sulfur oxides and particulate matter are allowed in Class II areas (Paulson et al. 1978). Class III is an optional designation allowing the most degradation of air quality. It permits States to choose areas in which to allow the most industrial growth.

The 1977 amendments declared as a national goal the "prevention of any future, and remedying of any existing, impairment of visibility in mandatory Class I Federal areas which impairment results from manmade air pollution." By 1979, the EPA must promulgate regulations, advise the States, and require SIP's containing emission limits and compliance schedules to make reasonable progress toward that goal within 10 to 15 years. Visibility protection may have substantial impact on long-range plans for forest burning because of the proximity of most forest lands to Class I areas, and the substantial impact of forest smoke on visibility. Visibility impairment, as defined in the amendments, includes "reduction in visual range and atmospheric discoloration," and may represent much tighter ambient standards for particulates than primary air quality standards.

Finally, in the Clean Air Act Amendments of 1977, Congress significantly broadened the authority and responsibility of Federal agencies in the following ways.

1. Each Federal agency, officer, or employee must comply with all substantive and procedural requirements imposed by any Federal, State, interstate, or local administrative authority or court.
2. Consultation with each State on its implementation plans, particularly regarding measures related to prevention of significant deterioration of air quality, and transportation controls, air quality maintenance plan requirements, and nonattainment requirements.
3. The Forest Service and other Federal land managers have been given "...an affirmative responsibility to protect the air quality related values (including visibility of any lands within a Class I area) and to consider... whether a proposed major emitting facility will have an adverse impact on such values."

These responsibilities require that Federal land managers also help manage the air resource, in partnership with other agencies. Wildlands must now be considered a receptor, as well as a source, of air pollutants.

RESEARCH REVIEW

Describing air pollution from wildland fire requires an understanding of both the production and transport of pollutants. Results of extensive research in both areas have been published in the last decade. However, considerable research is needed before smoke production or impacts can be measured and predicted on an operational basis.

Smoke Contents

The complexity of forest fires as emission sources begins with the complexity of the fuels consumed. Some prominent forest fuels with different chemical characteristics are: (Cramer 1974)

conifer duff	brush
conifer needles	grass
conifer twigs	herbs
conifer bark	moss
rotted wood—brown	lichens
rotted wood—white	sound wood
hardwood foliage	ferns

Cellulose, the major constituent, comprises approximately 50 percent of wood by weight. It is a high molecular weight linear polymeric chain of glucose units. Lignin comprises 23 to 33 percent of softwoods, 16 to 25 percent of hardwoods, and up to 65 percent of decaying wood. Like cellulose, lignin has a macromolecular structure, but is much more complex. Hemicellulose is a term given to a family of noncellulosic polysaccharides comprising 15 to 30 percent of wood, depending on species.

Extractives are not part of wood structure, but do contribute to flammability and to the complexity of combustion products. They include tannins and other poly-phenolics, oils, fats, resins, waxes, and starches. Extractives are present in wood in a range from 5 to 30 percent. Finally, ash-forming materials comprise from 0.1 to 3 percent of wood substance (U.S. Forest Products Laboratory 1974). These substances are present in nonwoody fuelbed components, but in differing proportions. Thus, measures of air pollutant emissions from forest burning can have meaning only if the presence and availability of these components is understood.

Two products of complete combustion, carbon dioxide and water, make up over 90 percent of the total mass emitted from wildland fires. Stoichiometric combustion of 1 ton of wood (containing 50 percent carbon, 6 percent hydrogen, and 43 percent oxygen) would yield 3,670 pounds of CO_2 and 1,080 pounds of H_2O. Roughly 7 tons of air, or 175,000 cubic feet, would be required.

Under field conditions, however, the presence of excess air and moisture, as well as inefficiences in heat transfer, creates a complex and unsteady set of thermal environments resulting in the emission of incomplete products that may pollute the air.

Although the origin of all the products of thermal decomposition cannot be assigned to individual components of fuel, it is known that each of the major components yields characteristic products. Thus, levoglucosan (tar) results from pyrolysis of cellulose, furan derivatives from pentoses, and an assortment of aromatic substances from lignin. The origin of much of the acetic acid is attributed to acetyl groups in wood (Browning 1963). At the elevated temperatures prevailing, secondary reactions of many types take place. The final products represent not only a wide variety of substances, but the proportions of these substances are variable depending on the conditions existing during decomposition. Thus, the thermal history, i.e., fire behavior, must be known in order to interpret or predict emissions.

Knowledge of the chemical and physical characteristics of emissions from forest burning was recently reviewed in detail by Ryan and McMahon (1976). Their treatment of the burning process and its relation to emissions is reproduced here:

> To appreciate how the components of smoke are generated, we need to recognize that fire is a two-stage process of pyrolysis and combustion. Although both stages occur simultaneously in moving fires, pyrolysis is the initiating stage of chemical decomposition that occurs at elevated temperatures. Most often it is viewed as a heat-absorbing or

endothermic reaction that destroys or decomposes large molecules into smaller ones. Fuel elements are separated into char and pyrolysate vapors that include high molecular weight hydrocarbon and particulate components. In addition, large complex organic compounds may be formed from smaller, free radical hydrocarbon species. Combustion is the rapid heat-producing or exothermic oxidation of the pyrolysate vapors escaping from the surface of the fuel.

Heat transfer in a bed of forest fuels is usually by radiation and convection. Since a typical fuel bed is composed of many types and sizes of individual fuel elements (leaves, needles, twigs, branches, logs, etc.) arranged in random fashion, pyrolysis and combustion proceed at several different rates through the bed. Generally, we try to group the total reactions of a moving fire front into three phases for ease of analysis.

Pre-ignition Phase (Pyrolysis Predominating).—In this phase the fuels ahead of the fire are heated; volatile components move to the surface of the fuel and are expelled in the surrounding air. Initially, these volatiles contain large amounts of water vapor and some noncombustible organics. As temperatures increase, hemicellulose followed by cellulose and lignin begin decomposing and release a stream of combustible organic products (pyrolysate). Because these gases and vapors are hot they rise, mix with the oxygen in the air, form combustible mixtures, and ignite—usually between 300° C and 600° C—producing the second phase.

Products of straight distillation, especially of volatile materials in foliage, conifer needles, bark, live tissues, and duff, also contribute to emissions in the preignition phase. Most of these substances are terpenes or closely related oxygenated compounds, borneol, and various aromatic aldehydes (Hall 1972).

Pyrolysis reactions and products from hemicellulose, cellulose, and lignin are described in depth by Browne (1963). The relative proportions of gases, vapors, tars, and charcoal and the relative proportions of flammable and nonflammable gases produced, vary widely according to the conditions of temperature, pressure, time, geometry, and environment under which pyrolysis occurs. Rapid heating through the range of active pyrolysis tends to produce less charcoal, much tar, and highly flammable gases that are rich in hydrogen, carbon monoxide, and hydrocarbons. Slow heating tends to produce more charcoal, little tar, and less flammable gases in which there is much water and carbon dioxide.

Kilzer and Broido (1965) describe competing mechanisms for the formation of cellulose pyrolysis products Levoglucosan (tar) is shown to likely be produced at relatively high (280 to 340° C) temperatures in an unzipping reaction. Lower heating rates, i.e., lower temperatures in the pyrolysis zone (200 to 280° C), favor the dehydration of cellulose, which produces more char, water, carbon monoxide, and carbon dioxide.

Continuing from Ryan and McMahon (1976):

Flaming Phase (Gas Phase Oxidation Predominating).—In the second phase the temperature rises rapidly from the heat of exothermic reactions. Pyrolysis continues but it is now accompanied by rapid oxidation, or flaming, or the combustible gases being evolved in high concentrations. Carbon monoxide, methane, formaldehyde, organic acids, methanol, and other highly combustible hydrocarbon species are being fed into the flame zone. The products of the flame zone are predominantly carbon dioxide and water vapor. The water vapor here is not a result of dehydration as in the preignition phase, but rather a major product of the oxidation of the fuel constituents.

Temperatures in this phase range between about 300° C and 1400° C or more. Some of the pyrolyzed substances cool and condense without passing through the flame zone, others pass through the flames but only partially oxidize, producing a wide range of products. Many products of low molecular weight (methane, propane, etc.) are produced as gases and remain gases as they move downwind; others, with higher molecular weights cool and condense to form small tarry liquid droplets and solid soot particles as they move from the combustion zone. These condensing substances, along with the rapidly cooling water vapor that is being evolved in

copious amounts, form the smoke that accompanies all forest fires.

Pyrosynthesis also occurs during this phase. Low molecular weight hydrocarbon radicals condense in the reducing region of the flames, leading to the synthesis of relatively large molecules such as the polynuclear aromatic hydrocarbons.

As long as gases pour forth rapidly enough to blanket the wood surface to the exclusion of oxygen, the charcoal formed during pyrolysis cannot burn and is left to accumulate. Since charcoal has only one-third to one-half of the thermal conductivity of wood, the layer of charcoal retards penetration of heat, and delays attainment of the exothermic point in the wood underneath. Thus, after the first vigorous flaming of wood, there is often a diminution of flaming until sufficient heat has passed through the insulating layer of char to pyrolyze deeper portions of the wood. The rate of consumption of large woody fuels is therefore determined largely by the rate of energy transfer within a solid rather than by the rate of pyrolysis (Browne 1963).

Ryan and McMahon (1976) add:

Glowing Phase (Solid Oxidation Predominating).—In the final phase of combustion the exposed surface of the char left from the flaming phase is oxidized, producing a characteristic glow. This continues, as long as temperatures remain high enough, until only a small amount of noncombustible minerals remain as gray ash. Many times the arrangement of the burning material is such that temperatures cannot be maintained, resulting in a black charred residue instead of the gray ash.

In an actual fire these different phases are difficult to discern because they occur both sequentially and simultaneously. Most observers of forest fires relate more readily to the terms flaming, or active, combustion and smoldering combustion. The flaming, or active, combustion obviously is associated with the visible flame front moving through the fuel. Smoldering combustion is a much more general and loosely-defined term and is associated with the so-called "die-down" phase after the main flame front has passed over the fuel. Smoldering combustion is a very smokey process in which dehydration, pyrolysis, low intermittent flame, and glowing processes are all occurring simultaneously with no one process predominating.

Ryan and McMahon continued:

Combustion Efficiency—It is important to emphasize that combustion in forest fires is not a chemically efficient process. One reason is that the moisture released from the fuels tends to absorb some of the heat energy from the fire, thus limiting combustion temperatures. The most important reason, however, is that wind, or air movement, in and around the fire, cannot bring enough oxygen to the combustion zone to mix efficiently with all the flammable gases produced. Air movement also moves from zones of high temperature at indeterminate times... .

Heading Fire.—A heading fire moves with the wind... . The flame front moves rapidly, burning with relatively high intensity, and moves quickly from fuel element to fuel element. Under these conditions most elements are not consumed completely before the main combustion zone moves ahead. A rather large zone of smoldering fuel is left behind.

Backing Fire.—A backing fire moves into the wind... . Since the flames do not move as rapidly, more of the individual fuel elements are consumed in the flaming zone. Thus, the smoldering time for the fuels is reduced and total combustion efficiency of the fire is increased.

Combustion Products

No reliable model exists for explaining the range in yield of combustion products from forest burning, although several fundamental thermochemical models have been proposed (Becker 1973, Stein and Bauske 1972) and empirical models presented (Sandberg and Pickford 1976, Sandberg 1974a). Until usable models are available to explain the variations observed, experimental results should be viewed as snapshots of forest burning emissions. The range of empirical evidence is reviewed here for each important pollutant.

Carbon dioxide (CO_2).—Carbon dioxide is not an air pollutant in the usual sense. However, it is

monitored because it is an indicator of burning efficiency. Vines et al. (1971) quantified the fuel consumed in wildfires by assuming that 3,660 pounds of CO_2 measured in the plume represents 1 ton of fuel burned. Emissions of between 2,000 and 3,500 pounds per ton have been reported in burning experiments (Ryan and McMahon 1976).

Carbon monoxide (CO).—Carbon monoxide is the most abundant air pollutant from forest fires. It may be a direct hazard to human health depending on duration, concentration, and the level of physical activity during exposure. Ryan (1974) measured concentrations as high as 200 parts per million (p/m) close to flames, but observed, as did Fritschen and his associates (1970), that the level was reduced to less than 10 p/m within 100 feet from the fire.

Laboratory measurements of CO yields from slash (Sandberg et al. 1975, Darley et al. 1966) and landscape refuse (Gerstle and Kemnitz 1967) have been reported in the range of 35 to 195 pounds per ton of fuel burned. Ryan and McMahon suggest that 500 pounds per ton could result from smoldering damp fuels, and Sandberg et al. (1975) measured CO emissions of 500 to 800 pounds per ton in very low intensity (less than 400 BTU/sq.ft./min.) laboratory fires.

The ratio of CO/CO_2 produced is an indicator of combustion efficiency. Fritschen et al. (1970) measured ratios in plumes through the range 0.024 to 0.072. Ratios averaged 0.034 during the active flaming phase, and 0.052 during residual combustion. Sandberg et al. (1975) reported an average CO/CO_2 ratio of 0.051 from laboratory experiments in ponderosa pine fuels.

Sulfur oxides (SO_x).—Most forest fuels contain less than 0.2 percent sulfur, so sulfur oxides could be produced only in negligible quantities in forest burning.

Sulfur dioxide (SO_2) is produced in large quantities by coal and oil combustion, oil refining, and smelting. Sulfur dioxide oxides to the sulfate ion (SO_4), constituting a major secondary source of atmospheric particulate matter. Visibility impairment in Class I Federal areas is probably caused mainly by urban sources of sulfate aerosols. Forest lands are also a major sink for atmospheric sulfur via the mechanisms of SO_2 absorption by vegetation (Murphy et al. 1977) and the occurrence of acid rains (Dochinger and Seliga 1976). Both air quality and productivity in wildlands may be affected by urban sources of sulfur oxides.

Oxidants.—It has been known for some time (Darley et al. 1966) that smoke produced by burning agricultural wastes contains minor amounts of ingredients liable to react in sunlight to form photochemical smog, typified by an ozone (0_3) concentration several times higher than the ambient background level of 0.03 parts per million (p/m). Evans et al. (1977) confirmed in airborne measurements that smoke plumes from forest fires generated ozone in concentrations up to 0.1 p/m after 45 minutes of irradiation. Radke et. al. (1978) measured 0_3 concentrations up to 0.9 p/m in plumes from broadcast slash burning.

Nitrogen oxides (NO_x).—Formation of nitric oxide normally occures through fixation of atmospheric nitrogen in the combustion zone at temperatures above 1540° C (Hall 1972). This is above temperatures normally occurring in prescribed fires. However, some NO_x may be formed at lower temperatures in the presence of hydrogenfree radicals, and nitrogenous compounds in forest fuels are another possible source of NO_x (Tangren et al. 1976). Information on nitrogen oxide emissions from forest fires is scanty and inconclusive.

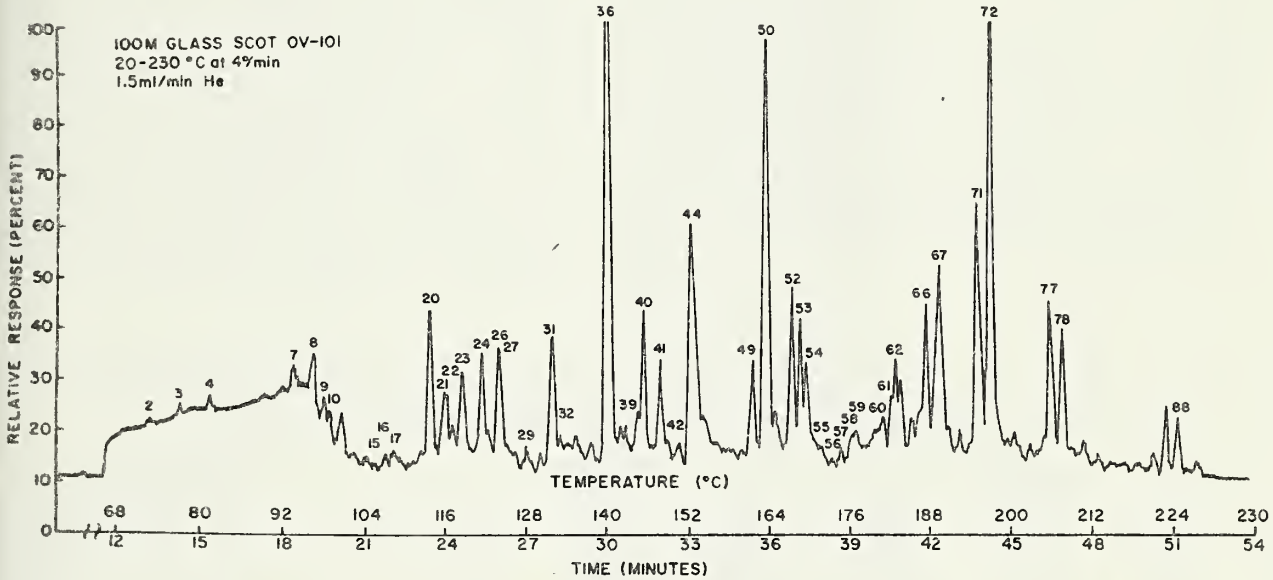
Hydrocarbons (HC).—Hydrocarbons are an extremely diverse class of compounds containing hydrogen, carbon, and sometimes oxygen. Air quality standards and emissions inventories usually lump all gaseous HC's together, although the majority of HC pollutants may have no harmful effect. On the other hand, trace constituents of the HC fraction of smoke may be the most important to photochemical smog production and to human health. Total HC's have been measured in the range of 10 to 40 pounds per ton of fuel burned (Ryan and McMahon 1976, Darley et al. 1966).

Unsaturated HC's are produced by incomplete combustion of organic fuels and have a high affinity for oxygen or other elements in order to saturate themselves. The proportion of saturated compounds, mostly methane, in slash fire smoke ranges from about 30 percent at peak fire intensity to about 15 percent in a smoldering fire. Low molecular weight olefins, especially ethylene, make up an additional 17 percent of total HC emissions from flaming fires and 3 percent from smoldering fires. Alkynes are produced in amounts similar to olefins (Sandberg et al. 1975).

In addition to the low molecular weight compounds already mentioned, there are literally hundreds of other organic gases and vapors in forest fire emissions. Ryan and McMahon (1976)

have begun to examine these emissions. Figure 1 is a chromatogram of organic vapors from a laboratory fire of loblolly pine needles. Only the intermediate range (principally C_4 to C_{12}) components were analyzed.

Included in this fraction are many oxygenated species (mostly organic acids, aldehydes, and furans) as one might predict from the fuel chemistry. It also includes many higher molecular weight, aliphatic and aromatic hydrocarbons such as would be expected from lignin combustion. Several low molecular weight oxygenated species, especially the carboxylic acids (formic and acetic acids, etc.) and the reactive aldehydes (formaldehyde, acetaldehyde, and acrolein, etc.), do not lend themselves to this type sampling procedure. They have been often reported as minor, but significant, constituents in the smoke of ligno-cellulosic fuels. Special procedures will be required to determine emission factors for those important compounds. (Ryan and McMahon 1976).



PEAK	COMPOUND
2	isopentane
2B	1-pentene
2C	furan
3	n-pentane
3A	isoprene
3B	acetone
4A	isopropanol
4B	cyclopentadiene
7	diacetyl
8	1-hexene
8A	methyl vinyl ketone
9	2-methylfuran
10	n-hexane
15	2,4-hexadiene
16	1,3,5-hexatriene
17	3-methylbutanal
20	benzene
21	cyclohexane
22	4-methylpentene
23	2,4-dimethylpentane
24	1-trans-2-dimethylcyclopentane

PEAK	COMPOUND
24A	sorbaldehyde (tent.)
26	2,5-dimethylfuran
26A	n-heptane
27	cis-2-heptene
29	2-vinylfuran
31	2,3-dimethyl-2-pentane
32	2,4-dimethylhexane
36	toluene
39	1-octene
40	2,3-dimethylhexa-1,4-diene
41	n-octane
42	2,3,5-trimethylfuran
44	furfural
49	ethyl benzene
50	p-xylene
50A	2-propionylfuran (tent.)
52	styrene
53	o-xylene

PEAK	COMPOUND
54	n-nonane
54A	2-isopropylfuran
55	anisole
56	2-methyl-5-isopropenylfuran
57	cumene
58	n-decane
59	camphene (tent.)
60	n-propylbenzene
61	m-ethyltoluene
62	p-ethyltoluene
66	1-decene
67	benzofuran
71	m-diethylbenzene
72	limanene
77	p-α-dimethylstyrene
78	n-undecane
88	n-dodecane

Figure 1.—*Chromatogram of organic vapors in loblolly pine smoke.* (from Ryan and McMahon 1976)

The occurrence of polynuclear aromatic hydrocarbons (PAH) in the combustion products of carbonaceous fuels is a well-known phenomenon. Several PAH's are known to be carcinogenic in animals. Benzo(a) pyrene (BaP) is the best known and studied of those classified by the National Academy of Science as strongly carcinogenic. Highly oxygenated compounds such as the carbohydrates are relatively inefficient and unimportant precursors to PAH compared to less oxygenated compounds.

Temperature plays a major role in PAH formation, with an optimum range of 700° C to 850° C. The formative mechanism of PAH in the pyrolitic/combustion production is known as pyrosynthesis, which is a buildup of carbon fragments into larger molecules in the reducing zone of burning fuels. Often, the thermal degradation process, rather than the chemical nature of the carbonaceous fuel, is the controlling factor in the production of PAH compounds (McMahon and Tsoukalas 1978). Airborne PAH, with its relatively high molecular weight and low vapor pressure, is believed to be emitted as vapor, but is adsorbed onto submicron particles as it cools and condenses (Ryan and McMahon 1976).

PAH production from laboratory burning of pine needles was measured by McMahon and Tsoukalas (1978), (tables 1 and 2). Heading fires appear to produce higher total particulate matter but lower PAH values than backing fires. Within heading fires, the flaming phase has relatively low particulate matter and PAH levels as compared to the smoldering phase. It appears that the longer residence times in backing and smoldering fires are more conducive to formation of five- and six-ring PAH compounds. More investigation is needed before the wide range of PAH levels is fully understood; thus, it would not be reasonable to generalize this pioneering work in an emission factor (Ryan and McMahon 1976).

Particulates—.Probably the most important single category of emissions is the particulate fraction of smoke. Particulates are the major cause of reduced visibility and serve as sorbtion surfaces for harmful gases that may be present. They may aggravate respiratory conditions in susceptible individuals, especially in combination with sulfur oxides.

Table 1.—*Polynuclear armatic hydrocarbons from burning pine needles by fire type (nanogram/gram of fuel burned; dry-weight basis)*[1] *(from McMahon & Tsoukalas 1978)*

Polynuclear armatic hydrocarbons	*Backing Fires*			*Heading Fires*		
	0.1 lb/ft²	0.3 lb/ft²	0.5 lb/ft²	0.1 lb/ft²	0.3 lb/ft²	0.5 lb/ft²
Anthracene/Phenanthrene	12,181	2,189	584	2,525	5,542	6,768
Methyl Anthracene	9,400	1,147	449	1,057	4,965	7,611
Fluoranthene	14,563	2,140	687	733	974	1,051
Pyrene	20,407	3,102	1,084	1,121	979	1,133
Methyl Pyrene/Fluoranthene	18,580	2,466	1,229	730	1,648	2,453
Benzo(c)phenanthrene	8,845	1,808	468	244	142	175
Crysene/benz(a)anthracene	28,724	5,228	2,033	581	543	836
Methylchrysene	17,753	1,891	877	282	1,287	1,559
Benzofluoranthenes	12,835	1,216	818	164	129	241
Benzo(a)pyrene	3,454	555	238	38	40	97
Benzo(e)pyrene	5,836	1,172	680	61	78	152
Perylene	2,128	198	134	33	24	46
Methylbenzopyrenes	6,582	963	384	65	198	665
Indeno (1,2,3-cd)pyrene	4,282	655	169	—[2]	—	—
Benzo(ghi)perylene	6,181	1,009	419	—	—	—
Total	171,750	25,735	10,249	7,632	16,549	22,787
			pound/ton			
Total suspended particulate matter (TSP)	21	9	5	20	73	118
			percent			
Benzene soluble organics	55	50	45	44	73	75

[1]Moisture content for all fires ranged between 18 to 27 percent.
[2]None detected.

The emission rate of particulates depends heavily on fire type, intensity, and phase. Heading fires produce about three times more total particulate than back fires (Ryan and McMahon 1976). For a given fire, emission rates during the smoldering phase can be eight times higher than in the flaming phase (table 2). Emissions per ton of fuel burned are approximately in inverse proportion to fire intensity; and fuelbeds with needles produce more particulates than woody fuels alone (Sandberg 1974b).

Published emission yields from several burning experiments are summarized in table 3. Laboratory fires are shown separately because they usually occur in simpler fuelbeds, i.e., without duff, live vegetation, rotten fuels, or fuel discontinuities. It is difficult, if not impossible, to reproduce the range of fuelbed conditions and fire intensities present in field situations. However, there is no clear difference in the results of laboratory vs. field experiments that is not overshadowed by differences between fuel and fire types.

Particulates from wildland fires are a complex mixture of soot, tars, and volatile organic substances (Ryan and McMahon 1976). The benzene soluble organic (BSO) fraction of particulates from forest fuels appears to be in the range of 40 to 75 percent compared to 8 percent in ambient air. The organic character of particulates also varies with fire type. Particulate from backing fires is black and sooty, while that from heading fires appears yellowish to dark brown and oily.

Air pollution effects from particulates depend heavily on particle sizes present. In general, particles below 0.3 micrometer and above 0.8 micrometer in diameter scatter light much less efficiently than those within this range. Fine particles (less than 3 micrometers) have a much greater impact than larger ones on human health (Burchard 1975), and BaP may be associated with the smallest particles from combustion sources (Ryan and McMahon 1976).

Table 2.—*Polynuclear armatic hydrocarbons from burning needles by fire phases (nanograms/gram of fuel burned; dry-weight basis)*[1] (from McMahon and Tsoukalas 1978)

Polynuclear armatic hydrocarbons	Heading Fires by Phases					
	Flamming	Smoldering	Flamming	Smoldering	Flamming	Smoldering
	0.1 lb/ft²		0.3 lb/ft²		0.5 lb/ft²	
Anthracene/Phenanthrene	1,612	7,049	865	9,046	2,351	8,791
Methyl Anthracene	539	3,872	667	8,193	1,909	11,447
Fluoranthene	445	2,317	244	1,516	622	1,331
Pyrene	750	3,078	342	1,454	888	1,291
Methyl Pyrene/Fluoranthene	455	2,383	494	2,501	1,036	3,396
Benzo(c)phenanthrene	228	397	77	189	179	173
Chrysene/benz(a)anthracene	472	1,324	230	769	628	980
Methylchrysene	263	497	343	1,989	466	2,290
Benzofluoranthenes	178	199	69	174	90	347
Benzo(a)pyrene	33	100	17	55	36	140
Benzo(e)pyrene	56	133	45	102	82	203
Perylene	38	33	14	32	27	61
Methylbenzopyrenes	19	397	52	304	75	1,069
Indeno(1,2,3-cd)pyrene	—	—	—	—	—	—
Benzo(ghi)perylene	—	—	—	—	—	—
Total	5,097	21,779	3,456	26,324	8,389	31,519
			pounds/ton			
Total suspended particulate matter (TSP)	13	55	11	165	31	222
			percent			
Benzene soluble organics	39	48	54	76	69	76

[1]Moisture content for all fires ranged between 18 to 27 percent.
[2]None detected.

Table 3.—*Summary of particulate emission yields reported from wildland fuels*

Fuel Type	Lab/Field Experiment	Particulates (pounds per ton of fuel burned) Type of Fire: Heading	Backing	Reference
Logging residues (Western)	Field	28–107		Sandberg (1974a)
	Laboratory		6–24	Sandberg (1974a)
	Field	≈80		Radke et al. (1978)
	Laboratory		4	Fritschen et al. (1970)
Landscape refuse	Laboratory		24	Feldstein et al. (1963)
Grass burning	Field		16	Boubel et al. (1969)
Live understory (Australia)	Field	14–40		Vines et al. (1971)
	Laboratory	28–40		Vines et al. (1971)
(Southern)	Field		15–30	Ward et al. (1976)
	Laboratory		24–97	Ryan (1974)
Pine litter Southern)	Field		45–55	Ward et al. (1976)
	Laboratory		6–29	Ryan and McMahon (1976)
	Laboratory	22–125		Ryan and McMahon (1976)

Feldstein et al. (1963) estimated that 50 percent of the particulate mass from the burning of land clearing debris is in the 50 to 100 micrometer size range. The estimates were derived from the examination of microscope slides placed around fires to collect fallout. However, Meland and Boubel (1966) measured smoke from field burning and found that particles were uniformly distributed in the submicrometer range. Haessler (1965) said that smoke particles, as initially formed, are usually about 0.1 micrometer. MacArthur (1966) collected particles from bush-fire smoke in a thermal precipitator. They ranged in size from 0.1 to 1.0 micrometer, with a marked preponderance at about 0.1 micrometer diameter. Vines et al. (1971) conducted extensive experiments. Using a variety of sizing techniques and aircraft traverses of smoke plumes, they found most of the particles collected appeared to be close to 0.1 micrometer diameter, and that smoke contained few particles larger than 5 micrometers. Some agglomerates of smaller particles were found as large as 50 micrometers. Two types of small particles were found. Spherical, smooth particles thought to be tar were 0.2 micrometer or more in diameter. Rough, crystalline ash and carbon particles between 0.05 and 0.03 micrometer were found to be less numerous than the tar particles. Butcher and Charlson (1972) reported that condensation of particles in flames produced submicrometer particles that may coalesce or agglomerate to clumps or chains before being emitted from the source.

Ryan and McMahon (1976) found that 91 to 95 percent of the particle mass was below 1 micrometer and 53 to 70 percent below 0.4 micrometer aerodynamic diameter in smoke from southern fuels. Sandberg and Martin (1975) found that 85 percent of particulate mass was less than 1 micrometer in diameter, and 69 percent less than 0.3 micrometer. Their scanning electron microscope studies classified particles into four types and showed that most single spherical submicrometer particles were approximately 0.1 micrometer in smoke from Douglas-fir fuelbeds. Ryan and McMahon (1976) also observed the number distribution of fires from a loblolly pine stand in North Carolina, a longleaf pine stand in Georgia, and a sawgrass stand in Florida. Their results, plotted in figure 2, were obtained from samples collected between 0.3 and 12 miles from the fires sites.

The close agreement between investigators strongly suggests that, regardless of fuel type, average particle size remains essentially constant near 0.1 micrometer (number distribution) or 0.3

micrometer (mass distribution). A few giant particles were produced and fall out near the fire site, but the similarity between laboratory, ground network, and aircraft samplers suggests that the size distribution does not change in the upper convection column or downstream in the plume.

Several general conclusions may be drawn from our current state-of-knowledge of smoke contents:

1. There are several different types of forest fires, each with distinct sets of emission characteristics. Emissions for combustion products vary

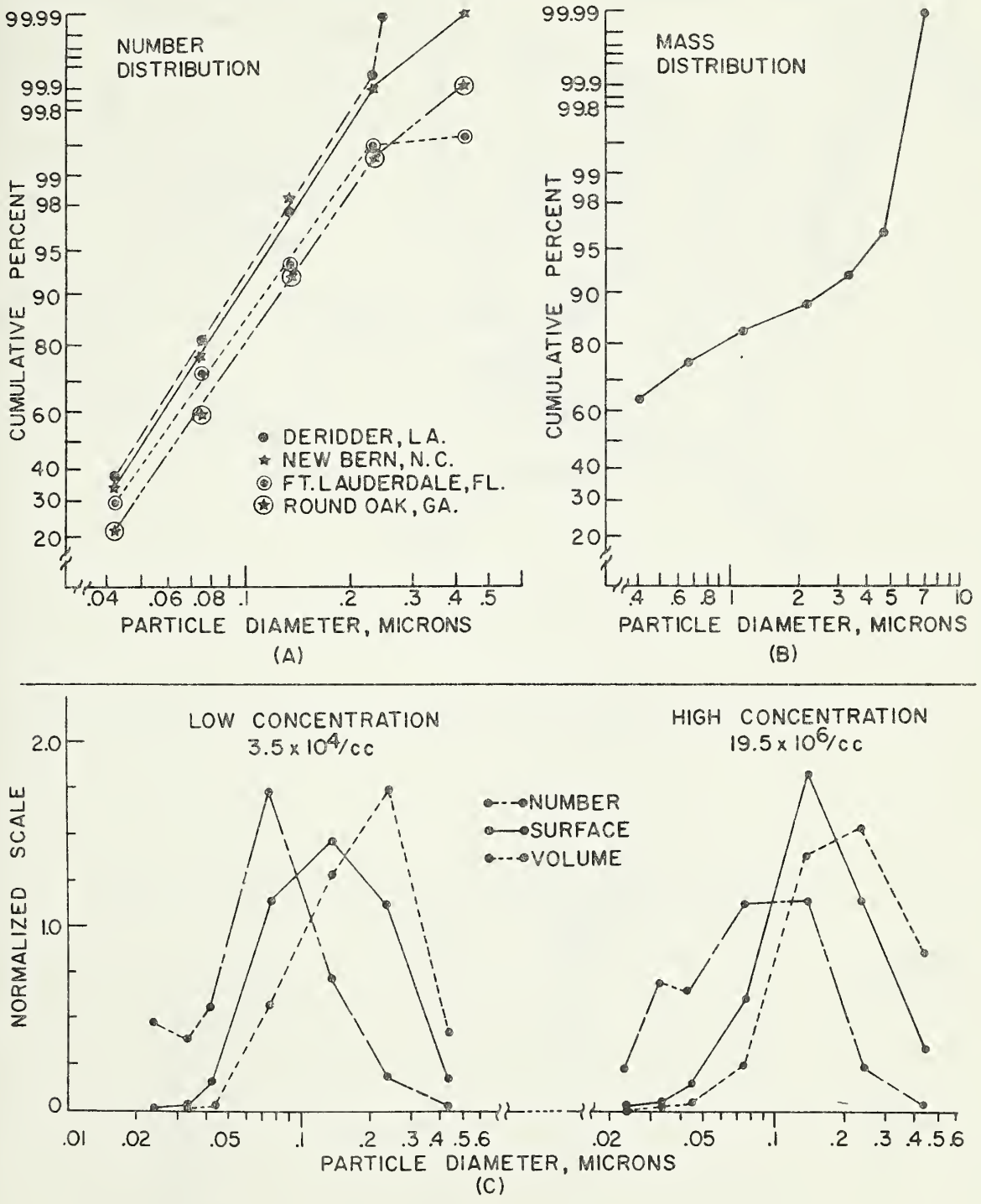


Figure 2.—*Particle size distribution:* A *Single fires in 4 fuel types;* B *Grand average, all fuel types; and* C *Normalized distribution, number, surface area and volume for a high and low concentration.* (from Ryan and McMahon 1976)

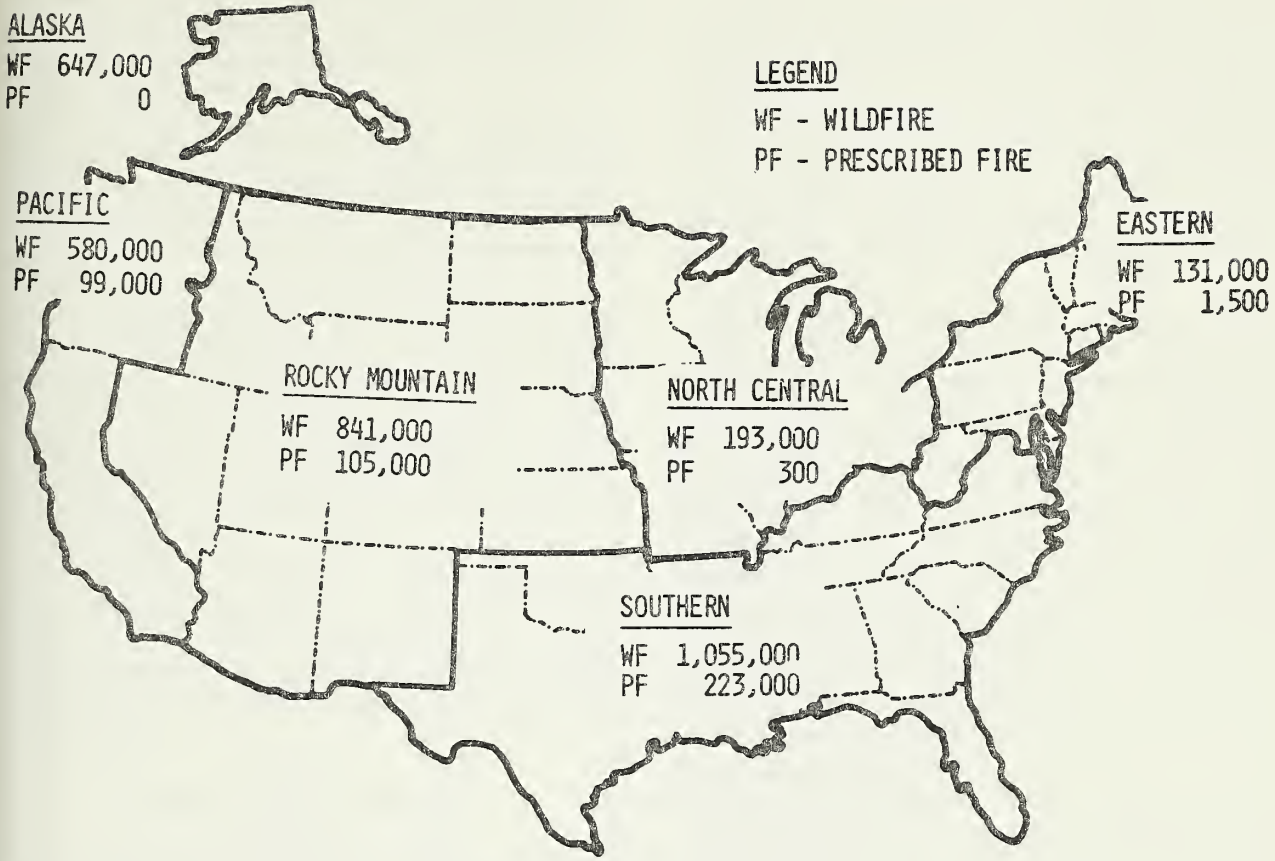


Figure 3.—*Annual forest fire particulate production by geographic region (tons).* (from Ward et al. 1976)

Table 4.—*Summary of average emission factors suggested for forest fuels*

Geographic	Fuel Type	Emission Factor (pounds/Ton^{-1}) Particulates	Hydrocarbons	CO	SO_x	NO_x	Reference
Nationwide	Open burning						USEPA(1972)
	- Agric. field	17	20	100	Neg.	2	
	- Landscape	17	20	60	Neg.	2	
	- Wood	17	4	50	Neg.	2	
National	Prescribed burn	17	24	140	Neg.	4	Yamate (1973)
National	Prescribed burn	50					Ward et al. (1976)
	Wildfires	150					
	Litter (backfires)	28–50					
	Logging debris	28–107					
Northwest	Prescribed burn	17–67	10–40	20–500	Neg.	2–6	Cook et al. (1978)

widely with fire behavior and fuel conditions. Low intensity fires, heading fires, and fires in nonwoody fuels produce the greatest yields of CO, HC, and particulate matter.

2. Water vapor and CO_2 comprise over 90 percent of the mass of combustion products from forest fires. The major impact of forest fires on air quality comes from minor and trace constituents. These are usually categorized under the conglomerate classes—hydrocarbons and particulates.

3. Within the hydrocarbon class, the low molecular weight gaseous species consist primarily of methane, ethylene, acetylene, and several hundred organic classes, i.e., organic acids, aldehydes, and furans. Many higher molecular weight, aliphatic, and aromatic hydrocarbons are also emitted. Benzo(a)pyrene has been found in wood smoke.

4. Forest smoke particulate matter has a very high organic character. The benzene soluble organic (BSO) fraction is between 40 and 75 percent as compared to ambient air, which averages 8 percent. Most particles are near 0.1 micrometer in diameter.

Emissions Inventory

An inventory results from a compilation of estimates of the level of activity of significant sources within the geographical area of concern, multiplied by an "emission factor" for each activity and each pollutant. An "emission factor" is a statistical average of the rate at which a pollutant is released to the atmosphere as a result of some activity divided by the level of that activity. Emission factors for forest burning have been, by convention, expressed as the pounds (or grams) of pollutant emitted per ton (or kilogram) of fuel consumed.

The sole purpose of emission factors is the compilation of emissions inventories. In general, they are not precise indicators of emissions from a single source, nor are they derived from a single investigation. A factor must represent the average pollutant production over the range of conditions included in the inventory.

A collection of national emission factors was published by the EPA (1972) to reflect laboratory and field experiments in agricultural, land clearing, and forest residues (Boubel et al. 1969, Feldstein et al. 1963, Darley et al. 1966, Gerstel and Kemnitz 1967, Fritschen et al. 1970). Yamate (1973) proposed a moderate increase in those factors to adjust for the unrealistically clean combustion of small laboratory fuelbeds (table 4).

Ward et al. (1976) proposed a major updating of particulate emission factors to represent the convergence of evidence from unpublished field and laboratory fires at the Forest Service Southern Forest Fire Laboratory and at the University of Washington. They proposed raising the national estimate from 17 pounds of particulate per ton of fuel burned to 50 pounds per ton^{-1} and 150 pounds per ton^{-1} from prescribed fires and wildfires, respectively.

Moyer, in compiling a Pacific Northwest emissions inventory for GEOMET, Inc. (Cook et al. 1978) suggests a high- and low-range estimate of emissions from prescribed burning in an approach analogous to reporting factors from controlled and uncontrolled estimates separately. The ranges were suggested by Ryan and McMahon (1976) and Sandberg (1974a). The range in emission factors represents the present uncertainty in assigning a national average source strength for prescribed burns, and is not intended to show the variation in individual fires. A prescribed fire could have a greater or lesser yield of pollutants, but the true national and regional average emissions probably are within the range shown.

The best published national emissions inventory for particulates is that presented by Ward et al. (1976). They estimate production of 3,500,000 tons of particulate per year from wildfires, and 430,000 tons per year from prescribed fires nationally. The area burned and fuel consumed in their inventory for each State were based on estimates by Yamate (1974), with some minor additions (fig. 3).

Unlike most sources, forest fires occur intermittently rather than continuously. Patterns of particulate production in each region are seasonal, depending on weather and fuel conditions. Figure 4, from Ward et al. (1976) shows the regional and seasonal distribution of emissions from wild and prescribed fires. The same pattern can be applied to gaseous emissions.

Cook et al. (1978) reported an annual average area burned by prescribed fire in Washington and Oregon for the period 1975-77. These estimates, from the States' smoke management reporting system, are two to three times greater than those by Yamate (1974) or Ward et al. (1976). Estimates of available fuel loadings also differed, but not significantly. Donoghue and Johnson (1975) reported on prescribed burn acres in the North Central States that were omitted by Ward et al. A summary of emissions estimates for criteria pollutants (excluding NO_x) combining the prescribed burn area estimates from all four sources with the high and

low emission factor estimates from Cock et al. (1978) is shown in table 5.

National emissions for particulates from prescribed burning are thought to be in the range of 178,000 to 701,000 tons annually; for total hydrocarbons 105,000 to 419,000 tons; for carbon monoxide 209,000 to 5,235,000 tons. Emissions of nitrogen oxides cannot be reasonably estimated at present. Comparison of emission amounts to those from other categories of sources would not be meaningful because of the uneven temporal and spatial patterns of emissions, and the usual remoteness of prescribed burning.

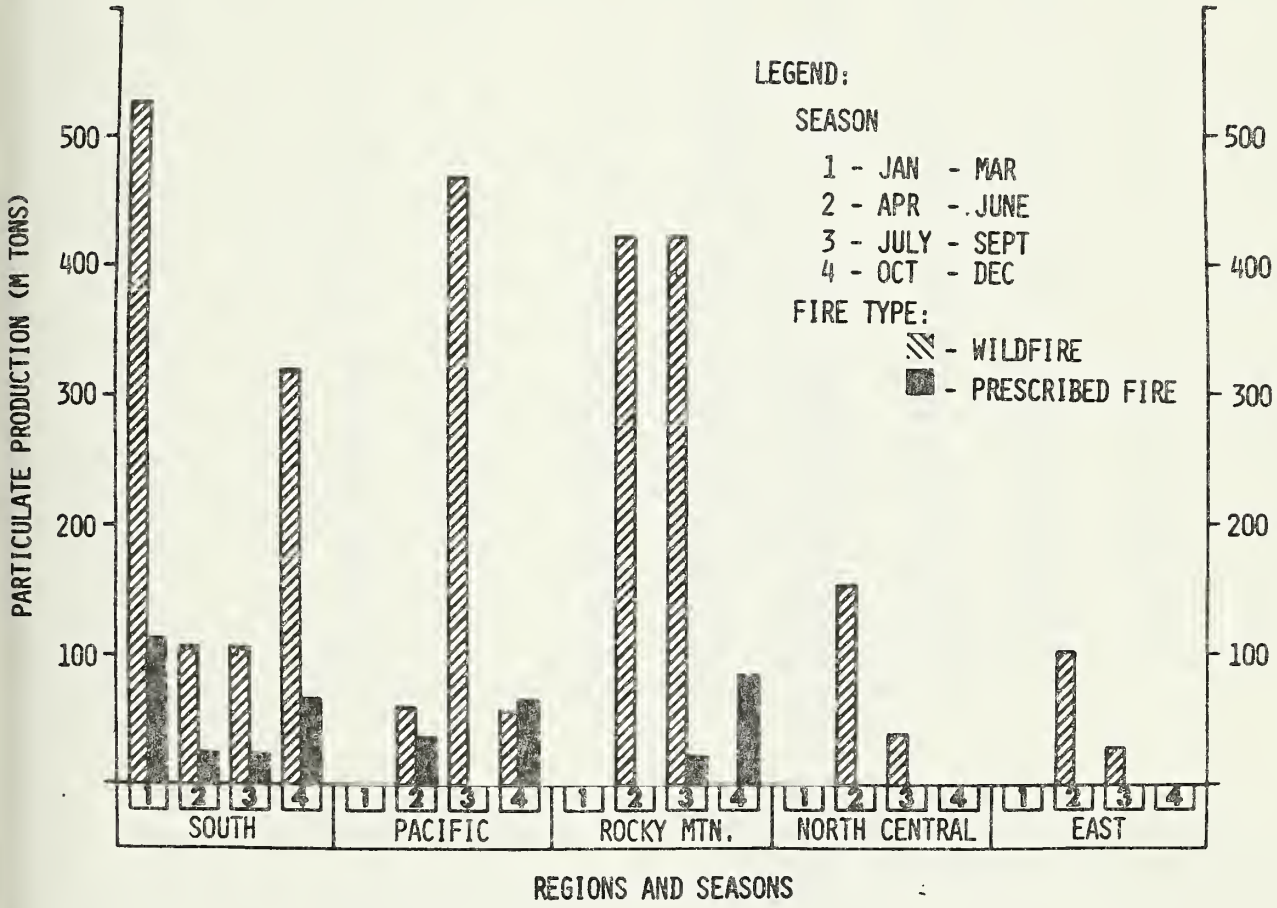


Figure 4.—*Forest fire particulate production by region and season.* (from Ward et al. 1976)

Table 5.—*Summary of prescribed fire acres burned and tons of criteria pollutant emitted (By geographic region, annual basis)*

States by Region[1]	Area (Acres x 10^{-3})	Fuel consumed (Ton/A)[2]	(Tons x 10^{-3})	Particulates @17 lb/Ton	@67 lb/Ton	Carbon monoxide @20 lb/Ton	@500 lb/Ton	Hydrocarbons @10 lb/Ton	@40 lb/Ton
California	12	70	847	7,199	28,374	8,470	211,750	4,235	16,940
Oregon	92	33	3,021	25,678	101,203	30,210	755,250	15,105	60,420
Washington	112	34	3,811	32,393	127,668	38,110	952,750	19,055	76,220
Total	216		7,680	65,280	257,280	76,800	1,920,000	38,400	153,600
ROCKY MTN									
Arizona	26	8	208	1,768	6,968	2,080	52,000	1,040	4,160
Colorado	3	8	21	178	703	210	5,250	105	420
Idaho	28	65	1,814	15,419	60,769	18,140	453,500	9,070	36,280
Montana	47	45	2,115	17,977	70,852	21,150	528,750	10,575	42,300
New Mexico	7	8	57	484	1,909	570	14,250	285	1,140
North Dakota	2	2	4	34	134	40	1,000	20	80
Total	113		4,218	35,853	141,303	42,180	1,054,500	21,090	84,360
N. CENTRAL									
Michigan	3	3	9	76	301	90	2,250	45	180
Minnesota	6	3	18	153	603	180	4,500	90	360
Wisconsin	7	3	20	170	760	200	5,000	100	400
Total	16		48	408	1,608	480	12,000	240	960
EASTERN									
Delaware	1	2	2	17	67	20	500	10	40
New Jersey	20	3	60	510	2,010	600	15,000	300	1,200
Total	21		62	527	2,077	620	15,500	310	1,240
SOUTHERN									
Alabama	209	3	626	5,321	20,971	6,260	156,500	3,130	12,520
Arkansas	55	3	164	1,394	5,494	1,640	41,000	820	3,280
Florida	719	4	2,876	24,446	96,346	28,760	719,000	14,380	57,520
Georgia	725	3	2,174	18,479	72,829	21,740	543,500	10,870	43,480
Louisiana	221	3	662	5,627	22,177	6,620	165,500	3,310	13,240
Mississippi	169	3	507	4,309	16,984	5,070	126,750	2,535	10,140
N. Carolina	117	3	352	2,992	11,792	3,520	88,000	1,760	7,040
S. Carolina	389	3	1,166	9,911	39,061	11,660	291,500	5,830	23,320
Texas	83	3	250	2,125	8,375	2,500	62,500	1,250	5,000
Virginia	31	5	159	1,351	5,326	1,590	39,750	795	3,180
Total	2,717		8,930	75,950	299,155	89,300	2,232,500	44,650	178,600
USA Total	2,958		20,938	177,973	701,423	209,380	5,234,500	104,690	418,760

[1]Excludes States with less than 1,000 acres burned per year or where data not available.
[2]From Yamate 1973.

Source Evaluation Methods

Measurement of pollutant emissions and transport from wildland fires is difficult and expensive. In this section, we will review the development of experimental and operational source evaluation methods.

Methodological Constraints

Open burning is a dynamic process affected by extreme variability within the several parameters affecting emission rates and transport and dispersion. Until mathematical models can be formulated and tested to better reflect changes of state with time, it is most convenient to deal with source evaluations in increments of steady-state, and in terms of probability that reflect normally expected consequences over a wide range of situations. Examples of steady-state application are found in the use of combustion stages and fire phases (S. For. Fire Laboratory Staff 1976). An example of probability over a wide range of situations is readily found in most transport and dispersion modeling, where Gaussian distribution has been widely applied (Turner 1970), and where expected variation in wind azimuth is reflected in dispersion spread angles (Pharo, Lavdas, and Bailey 1976). Source evaluations in the latter case best fit long-range planning and are most tenuous for case-by-case predictions.

Research methods, though often themselves constrained to some degree of incremental measurements, are directed toward acquisition of sufficient data points to ultimately permit the best time-dependent model adjustments.

Operational methods, on the other hand, must currently follow the more convenient larger increments and probabilities in arriving at source evaluations. Even though there are limits on the accuracy of case-by-case predictions, in total, all cases are better managed when the available operational systems are applied.

Research Methods

Research laboratory and field methods frequently employ similar apparatus. Smaller sizes of experimental fires in the laboratory are obviously different from laboratory and field experiments. This is in part because of the facility requirements, but also bears upon the need to limit variability. Within laboratory experiments, there is a greater degree of freedom to intentionally limit variables and variability. Further differences will be found in a greater number of data points obtained from laboratory experiments and in the real-time processing and integrations of these data, as opposed to field experiments. Most laboratory experiments call for subsequent field experimentation, and field experiments will frequently require returning to the laboratory to explain phenomena affecting predicted outcomes.

Laboratory experiments.—Laboratory methods have dominated forest burning source evaluations to date. The methods developed can best be categorized by the size of the combustion facility used.

"Test tube" or chamber experiments on a small scale—such as those conducted with thermo-gravimetric apparatus—permit both rapid replication and the isolation of single variables. These small-scale experiments are usually employed in detailed analyses undertaken to explain phenomena detected during larger scale experiments.

Intermediate scale experiments are well typified by "smog chambers," such as those located at the University of Florida and at EPA's Research Triangle Park. The Florida chamber has been used in forestry work on "secondary" emissions in which portions of a single pine needle and a small amount of organic soild have been used to study aerosol aging and photochemical reactions (Benner et al. 1977).

Larger scale hooded combustion facilities available for forestry research are generally patterned after work by Darley et al. (1966). The largest and most completely instrumented hooded combustion facility designed for forestry research is at the Southern Forest Fire Laboratory (SFFL). Two other facilities are Darley's at the University of California at Riverside and one contrived by Sandberg, Pickford, and Ward at the University of Washington. Similar combustion facilities, like those associated with aerospace studies, can be adapted.

Initial emphasis in these facilities has been on experiments relating "primary" particulate matter emissions to fuels and fire behavior; but "primary" gas sampling and detailed analysis of other "primary" combustion products are accelerating. A sequential sampler developed at the SFFL is of special interest to particulate matter sampling from the calibrated stack above hoods. By using a sampler of this type, incremental samples can be correlated with firephase and combustion stage. Wall losses and other experimental artifacts are of special concern to researchers using these facilities, and approaches such as grab sampling and laser beam measurements immediately above the fuelbed have been used.

Rate of fuel consumption is measured by fire spread markers (e.g., at leading and trailing edges of the flaming front) and by weight loss transducers. Automated data acquisition is employed with all sensors possible, but provision is made for post-experiment insertions of data from grab samples and filter traps, analyzed separately.

Work in progress.—In addition to the continuing and long-term laboratory work on smoke characterization, a study is underway at the SFFL to explore the correlations of CO_2 evolution, particulate matter emissions, and combustion rate. This study is of special importance because it has promise of yielding a research and operational tool that will greatly reduce the errors and costs of fuels and fire behavior measurements needed for all field research experiments and for operational methods.

Characterization work for polycyclic organic matter smoke constituents, such as that reported by McMahon and Tsoukalas (1978) and Jones (1975), can be expected to receive increased attention in view of the EPA Source Assessment in progress (see Prior Reviews). A gas chromatographic/mass-spectrometric capability in immediate association with one of the larger combustion facilities is believed an essential need for this work.

Field experiements.—Research field experiments fall in three categories of objectives:

1. Verifying laboratory results.
2. Developing and testing methods.
3. Obtaining estimates of emissions for operational use.

When all three objectives are assigned to an experimental series, resulting compromises usually impair objective 1. This further delays development of models that will best meet operational needs in the long run. As a consequence, current interest is shifting to increasingly greater emphasis on objectives 1 and 2, with objective 3 being met only as a possible spin-off benefit.

Current field experiments include nephelometer/mass and piezo/balance/mass correlations. Other experiments at the SFFL are now focused on methods of profiling plumes of intermediate height (±200 feet), using a tethered balloon from which a series of lightweight sensors are suspended.

The balloon experiments are an outgrowth of work done in a series of experiments using masts designed at the SFFL and reported by Ward (1974), as well as a series of experiments using sensors mounted in aircraft. In all three approaches (ballons, mast, and aircraft), it is possible to calculate a "window area" being sampled within the otherwise dimensioned plume; relate the measurements taken within the "window" to air flow rate measurements and to rate of fuel consumption measurements; and thus arrive a "source strength" (emission rate and/or factor) values for the fire under investigation. In addition to the obvious height advantages over masts, and to the fixed-point advantage over aircraft, the balloon method promises to yield data needed for downslope and downcanyon smoke transport applications.

Johansen[3] has described a combination of prefire and postfire inventories with extinguishment plots. In these, timed to match emissions sampling increments, prelocated plots are extinguished and subsequently remeasured to determine the amount of fuel actually consumed. The fuel inventory task is of sufficient complexity that special methods studies have been completed to provide operational systems, and others are in progress.

[3]Johansen, R.W. (Research Forester) [n.d.]. Data on file Southern Forest Fire Laboratory, Macon, Ga.

Operational Methods

Operational source evaluations are made to (1) make impact assessments; (2) predict, and modify as needed, the impact of single and series of prescribed fires; (3) confirm success or failure of smoke management measures being taken.

To date, forestry smoke impact assessments have been limited by very incomplete data on forestry emissions and fuels inventories (Ward et al. 1976). Predictive methods are similarly limited.

Atmospheric Transport

Pollutants emitted into the atmosphere are transported, diffused, and removed if they encounter anything capable of scavenging them. Transport and diffusion within a forest environment involves a surface meteorology that operates in nongeneral, nonrandom, highly irregular fashion. The magnitude of this surface flow and the scale over which it operates vary as a function of weather type, surrounding topography, and surface cover, and is often impossible to predict without detailed information. In addition, the presence of large roughness elements (trees) causes an unknown amount of pollution to be removed before it escapes to the above-canopy flow.

The major focus of airshed management activities will be prediction of the impact of alternatives. This impact must be measured by concentration and predicted by air quality models. Concentration is the mass of the pollution species per unit mass of air. It is a very irregular and nonhomogeneous variable throughout an airshed. Conceptually, it is possible to define an average of the concentration over the airshed, which we will call the "airshed concentration."

Airshed concentration is determined by the background (ambient) concentration of air entering the airshed, the emission of new pollution into the airshed, the transformation or removal of pollution within the airshed, and the volume of air available to mix with the pollution. Here, we concentrate on the question of available volume.

Meteorology determines the volume of air available to reduce the concentration of pollution between its point of emission and the location of air quality concern. This reduction is caused by turbulent air motions present in the atmosphere boundary layer. The depth of that layer, the so-called "mixing depth," represents one dimension of the available volume. Other dimensions of the volume

are determined by the intensity of turbulence and any effects of topography.

In this section, we discuss atmospheric turbulence and its effects on diffusion and dispersion, the mixing depth, and the interactions between these in developing the concept of available volume.

Atmospheric Turbulence

The normal state of the atmospheric boundary layer is one of disorganized, extremely complex turbulent motion. It is impossible to predict turbulent motions in detail. On a fine scale, this motion is random. It is, however, possible to predict likely outcomes or estimates of probable mean values. It must always be recognized, however, that these are no more than probability statements and are correct only on an average basis.

Consider an averaging process for the velocity, and extract a mean value and a deviation from that mean. Similarly, any contaminant introduced into the flow field can also be averaged, resulting in a mean and a deviation. Introduction of these variables into an equation expressing the conservation of mass results with

$$\frac{\partial C}{\partial t} + U_j \frac{\partial C}{\partial x_j} + \frac{\partial}{\partial x_j} \langle u_j c \rangle = S_0 - S_I$$

where, C, U_j, represent the average values of concentration and velocity; S_0, S_I, represent sources and sinks of the concentration; and $\langle u_j c \rangle$ is a vector representing the correlation between deviations of velocity and concentration from their mean values. The space derivatives in the equation account for the turbulent dispersion of emissions. It is obvious that dispersion consists of two terms: advection by the mean wind, and turbulent diffusion by deviations from the mean. The mean wind field determines where the pollution cloud will end up, while the turbulent correlation $\langle u_j c \rangle$ determines its concentration when it gets there. It is often difficult to distinguish these effects in practice. Precise measurements of wind fields are never available. At best, models of the turbulent correlation must make assumptions that restrict the generality of the term.

A comprehensive approach to turbulent dispersion is through the use of a multidimensional numerical model of turbulence (Fox and Lilly 1972), coupled with sophisticated simulation of the diffusion process (Boris and Book 1973). For virtually all realistic applications, however, it has become common practice to use the Gaussian model (Pasquill 1974) wherein

$$C = \frac{Q}{\pi \bar{U} \sigma_y \sigma_z} \exp\left(-\frac{y^2}{\sigma_{y^2}} - \frac{z^2}{\sigma_{z^2}}\right)$$

where σ_y, σ_z, are standard deviations of the diffusing plume in the perpendicular dimensions; Q is emission rate; and $\bar{U}$ is the mean wind. The equation is exact only for an unrealistically simplistic situation; however, through the use of empirically determined values for σ_y and σ_z, it has found successful application. Often these coefficients must be varied with time and distance to account for variations in the wind field and effects of differing atmospheric stability along the plume path.

Mixing Depth

The vertical distribution of temperature through the boundary layer determines the intensity of turbulent mixing. The depth of the boundary layer (the mixing depth) represents a limit to mixing air in the vertical because it is normally capped by an inversion and a stable layer above the inversion. Generally, under cloudless conditions, the boundary layer collapses after sundown due to the radiative cooling of the earth's surface. This leads to a cold air inversion slowly rising from the surface to a reasonably stable position about midnight. Cold air drainage in mountain locations complicates this cooling; however, the resulting stable layer is not substantially different.

With sunrise, the surface heats, causing instability in the layers near the ground and convection of this warm air into the cold air. Eventually, the layer heats until an adiabatic (neutral) profile within the boundary layer is established with an inversion separating it from stable air above. If one assumes a constant potential temperature within the boundary layer overriden by a warm air inversion and a stable lapse rate, the surface turbulent heat flux linearly decreases with height to the inversion base where the heat flux will be downward (negative) as a consequence of the entrainment of warm air (Tennekes 1973).

It is possible to develop equations for mixing depth. Details of the development can be found elsewhere (Tennekes 1973, Zeman and Tennekes 1977). It is sufficient to mention here that mixing depth may be determined by convection, i.e., surface heat flux, or by kinetic energy input. The presence of downslope/upslope winds in complex

topography might be such that convective flux cannot be ignored. Radiational flux must also be considered. The boundary layer temperature discussed by Sestak et al. (1978) could provide a necessary framework for such a model.

Dispersion Modeling

Dispersion modeling for short distances over simple terrain is well established (Turner 1970). Pharo and Hauck (1975) adapted Turner's model for prescribed fires, and to predict reduction in visual range. For distances greater than 10 kilometers from the source, the basic processes are established, but much uncertainty exists in the appropriate numerical coefficients to be used in the calculations.

Most operational dispersion formulations are based upon the Gaussian model. This concept has been developed for dispersion near the source (to about 10 kilometers), over reasonably smooth and regular topography, and for ground level releases (Pasquill 1974, Weber 1976, Pasquill 1976). Nevertheless, the air quality control community has been forced to utilize the approach well beyond its limits of proven accuracy for long-range dispersion up to 100 kilometers, over rough surfaces, mountainous terrain, and for tall stacks. Recently, EPA has attempted to introduce a degree of uniformity to such activities (Tikvart and Slater 1977).

Much of the model standardization discussion has dealt with complex topography (Argonne Natl. Lab. 1977). In addition, approximately 30 percent of the dispersion papers presented at American Meteorological Society meetings on diffusion and turbulence since 1974 (AMS 1974, 1975, 1976, 1977) have discussed this issue. The Department of Energy recently sponsored a workshop on this subject (Barr et al. 1977).

Considering all this material, three general points emerge for consideration in modeling dispersion over complex topography. The flow field in the mean is so complex over topography that it cannot be excluded in general, nor can it usually be well approximated by a single measurement point at the source. The solution to this difficulty is either very expensive monitoring for mountain dispersion, or a sophisticated model/data system such as the one outlined by Fox and Fosberg (1977).

If one is somehow able to resolve the indeterminate wind and temperature field problem, then considerations of the representativeness of normal turbulent parameterizations become an issue. Generally, this reduces to a discussion of which dispersion curves to use and when to use a box model approach. The box model seems most appropriate for contained mountain-valley complexes where a strong inversion is the rule rather than the exception. In such situations, strong radiatively induced local circulation systems distribute the pollution more effectively than does turbulence. These systems must be accounted for in any modeling that is done.

When the emission is at an elevation (or has an effective plume rise) such that it is free of the local flows, the Gaussian approximation may be acceptable so long as the proper coefficients for σ_y and σ_z are used. There is a lot of work currently addressing just this question. It seems that reducing the stability class, in the Pasquill-Gifford classification scheme as utilized by Turner (1970), by one grade; i.e., treating the flow as being one class less stable, approximates the actual dispersion in the vertical σ_z direction (Minott et al. 1977, Argonne Natl. Lab. 1977). Such a single statement cannot be made for σ_y at present. Other approaches to separate the plume dynamics from dispersion coefficients (Egan 1975, Fosberg et al. 1976) have been suggested.

Canopy Interactions

Our understanding of canopy flow is somewhat amenable to generalization. We have, for example, some approximations that suggest a qualitative relationship between biological density factors (leaf area index) and windspeed distribution. Such approximations must assume homogeneous cover characteristics and are one dimensional, i.e., they provide a profile of speed as a function of some above-canopy wind parameter. This type of relationship may be sufficient for certain climatological or planning considerations, but will not in general be satisfactory for real-time smoke predictions near the source. Progress has been made in a few locations at simulating the detailed micrometeorology of a forest canopy (Bergen 1974, Kinerson and Fritschen 1973). The role of canopies in scavenging pollutants is not well understood.

Transport Summary

In summary, three general knowledge areas (or scales) are identified:

1. *Canopy interaction.*—The canopy structure and energy flux within the canopy modify the characteristics of the emissions source.

2. *Atmospheric boundary layer.*—The mixing depth, surface roughness, atmospheric turbulence, and the shape of surrounding topography may determine available volume, especially in complex terrain.

3. *Mesoscale flow.*—Mesoscale meteorology, the interaction of multiple sources and air flows, and removal processes are important to understanding medium- to long-range transport.

Applicable research in each area has been reviewed. It should be recognized that the total research involvement required is substantially beyond the capacity of forestry research organizations, so that interaction with the meteorological community at large is essential. Specific topics for needed research are presented in the section on research priorities.

Smoke Effects on Forests

There are few studies on the effects of smoke on forest biota in the vicinity of fire or upon long-range transport and transformation. Smoke contains or results in the formation of a number of compounds, primarily oxidants (Cramer 1974, Evans et al. 1977), which are known toxicants to vegetation at relatively low levels. Speculation is that exposure of forest communities to smoke would result in some damage (Miller and McBride 1975). Duration of exposure is, of course, a critical factor in determining extent of injury (Jensen and Dochinger 1974, Dochinger and Jensen 1975).

The direct effects of smoke components on physiological processes may range from reduced photosynthetic efficiency in low doses to acute toxicity and tissue necrosis in high doses. On the other hand, some plants may actually increase photosynthetic rates in the field when higher CO_2 concentrations are sustained, as in a smoke plume (Green and Wright 1977). Periodic exposure to relatively high concentrations of SO_2 and oxides of nitrogen may have marked effects on tree growth and productivity (Stone and Skelly 1974); however, the overall growth impact of the broad range of oxidants is not well understood.

There is convincing evidence that several stages of the reproductive process in some conifers may be affected by oxidants (Houston and Dochinger 1977). While the effects of chronic exposure to anthropogenic pollutants may vary greatly from the effects of smoke from occasional forest burning, concentrations of SO_2 as low as 1.4 p/m have been shown to restrict pollen germ tube elongation (Karnosky and Stairs 1974). The indirect effects of smoke may also be an important concern since available evidence suggests temporary exposure to some pollutants could result in reduced host vigor and, therefore, reduced resistance to some insects and diseases (Hay 1975, Manning 1975). The importance of smoke effects on microorganisms should not be overlooked. In recent studies, it was strongly suggested that smoke from burning pine needles or grass reduced the growth, spore germination, and infectivity of several fungal pathogens; but for one common fungus, spore germination was enhanced (Parmeter and Urenholt 1975a, 1975b).

There is little information available on the effects of smoke on forest fauna. There is some suggestion that arthropod fecundity may be affected by some pollutants; however, it is unclear whether the effects are direct on the insect or indirect through the host substrate (Hay 1975).

Smith (1974) reported on the mechanisms by which anthropogenic pollution could affect the structure and function of a forest ecosystem (table 6). At a low level of pollutant concentrations, the vegetation and soils of temperate forests function as a very important sink for a variety of air contaminants. An intermediate dosage can gradually and indirectly influence species composition and productivity. A higher rate of contamination could grossly simplify the ecosystem and change hydrologic patterns. Smith reports few attempts to quantify such effects in field studies. However, because of variations in individual plant responses, caution must be exercised in extrapolating information from these data to describe probable interactions between plants and forest fuel combustion products. Undoubtedly, forests act as a sink for these products; however, no direct effects on green plants have been demonstrated except for CO_2 as noted earlier.

Available evidence suggests there is much we need to know about the direct biological effects of primary combustion products in smoke on forest organisms. Currently, ozone is the only known secondary product of smoke that may have direct effects on green plants. Even here, ozone synthesized in smoke plumes may be partitioned from susceptible vegetation by turbulent mixing typical of plumes and good burning conditions. Research efforts on the distribution and effects of primary and secondary pollutants from forest smoke must be expanded if we are to provide comprehensive analyses of the impacts on forests.

Table 6.—*Influence of air pollution on temperate ecosystems*[1]

Air pollution load	Response of vegetation	Impact on ecosystem
Low	1. Act as a sink for contaminants	1. Pollutants shifted from atmospheric to organic or available nutrient compartment
	2. No or minimal physiological alternation	2. Undetectable influence, fertilizing effect
Intermediate	1. Reduced growth (a) detruded nutrient availability (i) depressed litter decomposition (ii) acid rain leaching (b) suppressed photosynthesis, enhanced respiration	1. Reduced productivity lessened biomass
	2. Reduced reproduction (a) pollinator interference (b) abnormal pollen, flower, seed, or seeding development	2. Altered species composition
	3. Increased morbidity (a) predisposition to entomological or microbial stress (b) direct disease induction	3. Increased insect outbreaks, microbial epidemics Reduced vigor
High	1. Acute morbidity	1. Simplification: increased erodibility, nutrient attrition, altered microclimate and hydrology
	2. Mortality	2. Reduced stability

[1]From Smith 1974.

RESEARCH APPLICATIONS

There are at least three distinct applications and groups that use forest burning/air quality information and would benefit from additional research. The applications and user groups are as follows:

1. Designing control strategies to protect health, maintain or improve visibility, and meet ambient air quality standards. State agencies have the responsibility and authority to place constraints on emissions and/or pollution from prescribed fire.

2. Operating smoke management systems that apply control technology to prescribed burning emissions and schedule burns to minimize air quality impacts. State or Federal agencies, variously by agreement, have smoke management coordinating responsibility, while National Forest Ranger Districts and their counterparts have the responsibility for implementation.

3. Completing land management plans. The atmosphere is a resource that can be managed, has measurable outputs and measurable constraints, and is affected by management decisions regarding other wildland resources. The land use planning process is the obvious framework for interrelating goals and alternatives for timber production, fire management, and air resource management.

These applications and the necessary information flow systems are diagrammed in figure 5. Each component will be discussed separately in the remainder of this section.

Emission Control Strategies

State and Federal environmental agencies make independent decisions having tremendous impact on forest productivity and economics. Control strategies are at present based on perceived, rather than measured, impacts of forest burning on ambient air quality, visibility, and human health. Mounting political pressure, and sometimes indiscreet use of limited scientific knowledge, is forcing more attention on forest burning. In general, a quantitative system of inputs would lead to more rational control strategies and provide evidence to counter unwise regulation.

The States are responsible for writing implementation plans (SIP's) and/or attainment plans that identify the emission sources to be controlled or curtailed. Most States granted variances from air pollution control rules to valid forestry burning

practices in 1972. However, emissions from major stationary sources have been reduced, and nonpoint sources are likely to receive much more attention in the SIP's for AQMA's and for Class I visibility areas. Forest and range burning is much more vulnerable to regulation than ever before.

Control strategies outlined in SIP's are usually based on an analysis of the relative contribution of all source categories (including forest burning and agricultural field burning in addition to transportation, industrial, fuel combustion, and residential sources) to (1) total emissions within an AQCR, (2) criteria pollutant concentrations within an AQMA on days exceeding ambient standards, or (3) concentrations of noncriteria pollutants presenting a special health hazard. Only the first approach, i.e., an emissions inventory, is required by the Clean Air Act.

Emissions Inventory

An inventory results from a compilation of estimates of the level of activity of significant sources within the geographical area of concern, multiplied by an emission factor for each activity and each pollutant. The sole purpose of emission factors is the compilation of an emissions inventory, and they must represent the average pollutant production over the range of conditions included in the inventory.

Emission factors for forest burning have been, by convention, expressed as the pounds (or grams) of pollutant emitted per ton (or kilogram) of fuel consumed. Those units are the most easily measured and reported in burning experiments, so their use is natural in emission factors. Conceptually, dimensions should be chosen such that the mass of emissions are closely correlated with the dimensions used to express the level of activity over the range of burning conditions. For example, Yamate (1973) used an emission factor with dimensions of pounds per acre for assessing emissions from wildfires. Sandberg and Pickford (1976) suggested that the level of burning activity be measured in acre-hours to reduce the error caused by variability in fire intensity. Other dimensions are possible, and deserve consideration.

The level of activity, usually tons of fuel burned, has equal importance with emission factors in estimating emissions. Since all fuels are seldom consumed in a fire, estimating the amount of fuel actually consumed (available fuel) is often difficult. Uncertain estimates of fuel consumption probably cause more errors in emissions inventories than do estimates of emission factors. Fuel consumption is often overestimated in compiling emissions inventory. States operating smoke management reporting systems compile, from local managers, daily estimates of tons of slash burned. In most cases, the estimates of available fuel are made without inventories, and months in advance.

Total fuel loading is frequently reported in place of available fuel estimates.[4] A widely cited inventory by Yamate (1974) used the total fuel loading in National Fire Danger Rating System (NFDR) fuel models as the basis for estimates of available fuel (Yamate 1973). Only the Southern Region, by virtue of the Southern Forestry Smoke Management Guidebook (SFSMG) (Southern Forest Fire Laboratory Staff 1976), has the software necessary to make reasonable estimates of available fuel.

Emissions inventories in 1978 will, in most cases, show a much greater contribution for forest burning, relative to other sources, than the inventories completed ca. 1968 and ca. 1972. Partly as a result of prior control of other source categories and partly because of errors in earlier inventory procedures, forest burning will receive more attention in the control strategies of some States in the future. Moreover, the proximity of forest burning to Class I areas will remove the advantage of forests being "remote" sources.

Impact Assessment: Criteria Pollutants

The Clean Air Act sets standards for ambient air quality, not for emissions. Emission control strategies to attain (or maintain) ambient air quality are most efficient when directed at emission sources contributing significantly to pollution on days when standards are violated in AQMA's (and in the future, for Class I visibility areas). Emission sources, such as forest burning, remote from AQMA's should have less impact than resident sources on ambient quality, especially when fires are scheduled to avoid such impacts. Control strategies based on impact assessment rather than emissions inventories, therefore, should be less concerned with remote sources such as prescribed fire.

[4]Hedin, Al. (Smoke Management Coordinator). 1978. Personal conversation. Washington State Department of Natural Resources, Olympia, Wash.

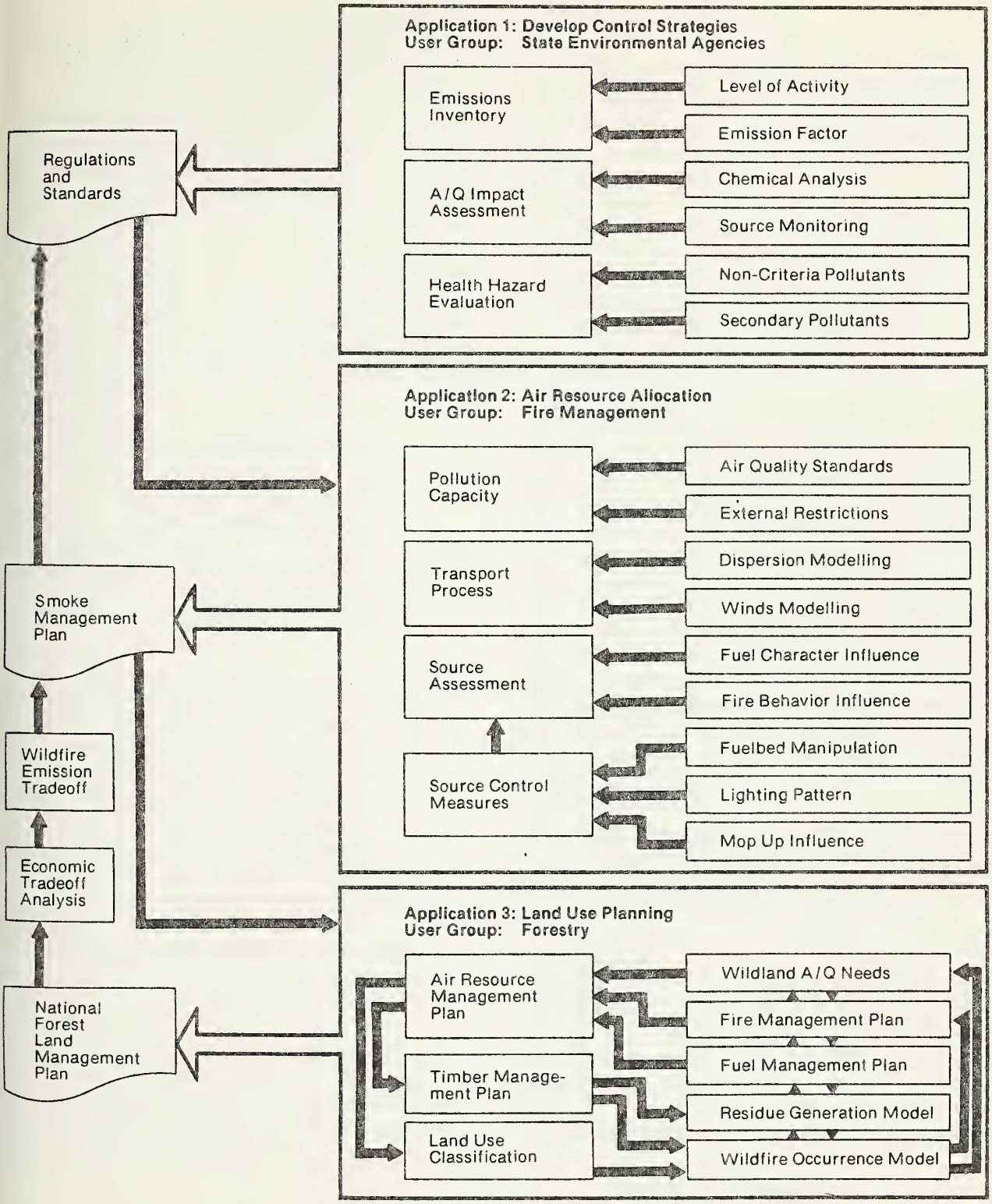


Figure 5.—*Applications of forest burning—air quality research.*

Impact assessments may be accomplished through air quality monitoring procedures following plumes from source to receptor, or through chemical analysis of ambient air to identify sources via signature compounds unique to each source. The current technical uncertainty and expense of either method has precluded their use in setting control strategies where forest burning is an important source. These uncertainties are sensitive to research input.

Pierovich[5] proposed an airborne monitoring scheme to assess the impact of prescribed fire smoke on air quality in selected AQMA's. The proposal, under consideration by the EPA and the National Wildfire Coordinating Group, would provide information on:

1. Concentrations of particulate matter and other key constituents within plumes over impact areas.

2. Ground-level impact area correlations with tracked plumes (Piezo balance application).

3. Preliminary emission rate data for example fires. The Siuslaw National Forest, Oreg., routinely uses noninstrumented aircraft to track plumes and qualitatively assess their impact on population centers.

Hidy (1974), under contract with California, successfully used chemical analysis of filtered particulates to identify many of the sources contributing to ambient concentrations of particulates by measuring trace molecular constituents associated with the aerosols emitted from each source. The Oregon Department of Environmental Quality (ODEQ) expects to use the same approach in 1978 for determining the relative contribution of agricultural burning, forest burning, residential heating, transportation, and industrial sources in the Eugene-Springfield AQMA. Much of their success depends on finding a reliable "signature" compound in the sampled particulates that identifies field and forest burning.[6]

The successful identification of a signature compound would benefit both the pollution control agencies and the proponents of prescribed forest burning. To date, only minor research effort has been devoted to this problem.

[5]Pierovich, J. M. (Program Manager). 1978. Proposal on file Southern Forest Fire Laboratory, Macon, Ga.

[6]Core, John. (Supervisor, Air Quality and Monitoring). 1978. Personal conversation. Oregon Department of Environmental Quality, Salem, Oreg.

Health Hazard Evaluation

The Clean Air Act, in addition to requiring ambient air standards for criteria pollutants, empowers the EPA to establish national emission standards for hazardous air pollutants. Section 112.(a) of the Act states:

> The term "hazardous air pollutant" means an air pollutant to which no ambient air quality standard is applicable and which in the judgement of the Administrator causes, or contributes to, air pollution which may reasonably be anticipated to result in an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness.

No emissions from forestry burning have yet been defined by the EPA as hazardous, and no threshold limit values have been set for compounds in forest smoke. However, emissions of polycyclic organic matter (POM) have been reported from burning pine needles (Ryan and McMahon 1976), from agricultural burning (Darley and Lerman 1974), and from virtually all other combustible sources. Some concern has been shown by the city of Eugene, Oreg., (Smith 1978) over the carcinogenic fraction of POM from forest burning. That concern may grow to State or national significance and receive attention in drafting control strategies. Substantial additional research would be needed to identify and predict possible health impacts of prescribed fire.

Health impacts studies for forest burning have been proposed using three approaches: epidemeology, ambient air sampling, and simulation modeling. Only minor research effort has been directed at the question, and no definitive work has been completed.

The Montana Air Pollution Study[7] is looking for some correlation between the level of burning and mortality from chronic upper respiratory disease (especially emphysema and bronchitis). Followup interviews are being undertaken to isolate other causal variables, and air quality monitoring has been started to establish cause-effect relationships.

Smoke Management

Smoke management is the application of technology to minimize air quality impairment from

[7]Haddow, Dennis. (Air Pollution Control Specialist). 1977. Personal conversation. Montana Department of Health and Environmental Sciences, Helena, Mont.

prescribed burning. The practice includes fuel management and fire prescriptions that reduce available fuel loadings or improve combustion efficiency; firing and mop up techniques that reduce emissions; scheduling that enhances convection or dispersion; scheduling that ensures plume trajectory away from sensitive areas; and coordinating sources for the best overall result. The central principle of smoke management is to "avoid overloading natural clearance mechanisms—both pulmonary and environmental" (Pierovich 1976).

Smoke management programs are part of the Forest Service Manual in all Regions. The rigor and complexity of the plans reflect the levels of burning activity and environmental concern locally. The Eastern, Rocky Mountain, and Alaska Regions face very high environmental concern, but little prescribed burning. Smoke management in these regions is based on good communication and cooperation with air pollution authorities. The Northern, Intermountain, and Southwestern Regions are in an intermediate stage and are developing more rigorous plans. The Southern Region, with the preponderance of burning there, is guided by a voluntary decision procedure (Pierovich et al. 1976).

Burning activity is moderate in California, where a burn-no-burn day system is administered by the Air Resources Board (Morgester 1976). The States in the Pacific Northwest Region operate complex cooperative smoke management systems (Washington Department of Natural Resources 1975) that coordinate, restrict, and monitor impacts of burning based on meteorological conditions.

It should be realized that most pollution sources are not permitted the opportunity to utilize a meterologically oriented pollution control concept. The extent to which forestry will be able to operate such systems is unclear, and will be decided largely by State air control agencies. The EPA has, in fact, disallowed such intermittent (or supplemental) control procedures for major sources. Fortunately, forest burning is a temporary source and, as such, is not subject to consideration under the PSD regulations. Continued enjoyment of such a classification will require careful management.

Smoke management, in the context presented here, has two modes of application with two user groups for research information. In the air resource allocation mode, a user makes an assessment of emissions source strength and potential air quality effects, estimates the capacity of atmospheric clearance mechanisms, coordinates multiple emissions sources, and allocates the air resource by making go-no-go decisions on planned burning operations. The user, as defined by the smoke management plan, may be the forester (as in the South), the State Forester's Office (as in the Pacific Northwest), or an officer of another agency (as in California). In the source control mode, the user is the fuels management officer who applies techniques to limit emissions. The functions of user groups, and their research and development needs, are broadly defined herein.

Air Resource Allocation

The air resource allocation approach is based on using predetermined acceptable levels of air quality along with predicted meteorological dispersion in order to calculate the maximum allowable source emission that can be accommodated on any given day. The basic air resource allocation model concept was developed for land management planning (Fosberg and Fox 1977, Fox and Fosberg 1977). The system requires a geographical matrix of information about acceptable concentrations (regulations, background levels, external factors), transport processes (winds, dispersion, secondary processes), and source assessment (emissions rate, control factors, plume rise). The system output is an allowable burn matrix that defines the level of activity tolerable in a given area. The concept was used by Pharo et al. (1976) and Pierovich et al. (1976) in the guidebook, for the simplest case in terms of transport processes.

Pollution capacity.—The ability of the atmosphere to accept additional pollutants, in the simplest case, is the shortest term ambient air standard (or visibility standard) minus the background concentration in the affected area. It is more difficult to determine the acceptable concentration if a long-term (e.g., annual) ambient standard is limiting. Internal restrictions may also prevail. For example, western Oregon National Forests have a self-imposed limitation during the 60 days of peak agricultural field burning activity.

The decision logic advanced by Pierovich et al. (1976) includes a procedure for subtracting back ground particulate concentrations (estimated from visual range) from acceptable concentrations to calculate pollution capacity. The regulatory agencies in Western States input a simple yes/no criterion based on actual or expected nonattainment in AQMA's. If air quality standards are violated in

one or more populated areas, all open burning is disallowed without regard to transport or source characteristics.

Transport processes.—Wildland fires are usually remote from the centers of population that require clean air. Most fires in Western States are also higher in elevation than the smoke sensitive areas. Smoke concentrations are, thus, greatly reduced by the turbulent diffusion processes and removal mechanisms discussed in the research review section. A dilution factor translating the acceptable rate of pollutant addition at the sensitive area to the acceptable rate of emissions at the source must be calculated in some way. That dilution factor may range from zero, where the plume is confined in a narrow valley with a low mixing depth, to 100 percent where advection is away from the receptor.

Currently, in lieu of modeling capability, transport and dilution estimates are made intuitively by forest managers and smoke management coordinators. Removal mechanisms are ignored. Failures of smoke management plans, i.e., serious smoke intrusions into sensitive areas, are by definition failures to predict plume trajectory and dispersion. On the other hand, because of the need to be conservative when uncertain, burning is frequently disallowed on days when no air quality problem might develop. Improved transport prediction would reduce air quality impacts while at the same time increasing allowable burning days.

Smoke management systems in the West (Washington Department of Natural Resources 1975) place restrictions on tonnages of consumable slash when burning is done within 60 miles of disignated areas (DA), and advection is towards the DA. Mixing depth, i.e., whether more or less than 3,000 feet, is also used to determine tonnages to be burned. Southern foresters may use the adaptation of Turner's (1970) workbook by Pharo et al. (1976) to predict dispersion over flat terrain. Dilution is calculated from stability classes, transport windspeeds, and fire heat release rate. The technique is not directly suited to long- or medium-range transport nor to complex terrain.

Substantial new research is required before wind fields and dispersion can be adequately modeled to meet smoke management requirements. No other aspect of air resource allocation represents as great a gap in our present knowledge.

Health hazards of prescribed fire smoke may be aggravated by the adsorption of toxic substances on the particulate matter emitted. Secondary reactions and processes occurring in the convection column or plume are not well understood and are not now factored into air resource allocation decisions. New research is necessary to adequately predict the chemical fate of primary emissions from forest burning and their interaction with other aerosols.

Source assessment.—Once the geographical matrix of allowable emissions has been generated by capacity and transport analysis, the potential emissions source strength of a planned burning operation must be assessed before a go-no-go decision can be reached. Source strength has been shown to vary widely as a function of fire intensity (Sandberg 1974a), species (Darley 1976), fuel size, arrangement, and condition (Tangren et al. 1976), as well as firing technique (Ward et al. 1974). Because of this complexity, and the extremely wide range of emission rates possible from prescribed fires, very little capability exists to predict or model source strength.

Johansen et al. (1976) recognized the importance of separately assessing sources during the convective lift and nonconvective lift phases without considering active and residual combusion; and without using fuel type conditon, and arrangement in estimating emissions rate. However, even for southern fuels, the important fuel types not considered in their approach, and the lack of specific information available to support the approach define a considerable research need.

Regions outside the South use only crude estimates of emissions source strength for smoke management. Generally, an estimate of fuel loading is the only input to source assessment. Emissions are assumed to be proportional to tons of fuel consumed under all fuel and fire conditions. Most smoke management systems restrict only the amount of fuel treated by prescribed fire, rather than emissions. Consumption in components of the fuelbed other than downed woody fuels is ignored. Moreover, no reliable algorithm to predict fuel consumption in any fuelbed component is available.

A considerable array of research in source assessment would be necessary to support a quantitative smoke management system. Inventory equations for nonwoody fuels are necessary. Consumption prediction systems for all components are lacking. Emissions yield from duff components and live fuels must be measured. Emission rates for residual combustion must be quantified. Predictors and estimates of the proportion of fuels consumed

during active, residual, convective, and nonconvective lift phases are required. Models that further quantify the effect of fuel condition and fire behavior on emission rates are inadequate at present.

Source Control

The fire manager has substantial control over the mass and rate of pollutants released from prescribed fire. The control factors are embodied in the general relationships of fuel consumption fire behavior-emission rate discussed in the last section. Qualitative guidelines to good scheduling and firing practices are available (Pierovich et al. 1976, Sacket 1976, Tangren 1976, Cramer and Graham 1971). These guidelines encourage well-cured fuels, backing fires, rapid ignition, afternoon firing, YUM-yarding, avoidance of fuel concentrations, rotten logs, snags, and aggressive mop up. Unfortunately, these guidelines can conflict with other objectives. If strictly followed, they would reduce prescribed burning accomplishments and increase burning costs.

In most cases, the manager is provided no tangible incentive for practices that reduce emissions. Because air resource allocation is qualitative, and because restrictions are based on tons of fuel treated, no benefit is provided to offset the additional costs. It would be reasonable to allow a manager more opportunities to treat fuels in return for reducing emissions, but that would require quantitative source assessment. Research needs for source control are identical to those for air resource allocation.

Southern forestry is unique in that the fire manager is given the dual responsibility for source control and air resource allocation, according to the decision logic provided by Pierovich et al. (1976). The arrangement has the favorable influence of providing incentives for source control not provided elsewhere.

It is well understood that a program of hazard reduction amounts to control technology for wildfire smoke (Cooper 1976). However, most regions have not compiled the information needed to quantify this benefit of prescribed fire. Moreover, wildfire smoke is usually considered a "natural" source by air pollution control agencies, while prescribed fire smoke is "manmade" and subject to regulation. Research and development to quantify the benefits of hazard reduction, if an offset were allowed for controlling natural sources, would enable better forest managment as well as cleaner air.

In this section, we have attempted to describe air resource allocation and emissions source control in their present qualitative context and in their conceived quantitative state. Cooperative smoke management systems have developed in response to environmental concern and the continued need to use prescribed fire in forest management. Smoke management has been effective in greatly reducing the impact of forest smoke on densely populated areas. To the extent that air quality and emissions standards increase in applicability to forest burning, an increasingly quantitative smoke management system will be required.

Land Use Planning

Clean air is a renewable resource for which assessment and planning is required by the Forest and Rangeland Renewable Resources Planning Act of 1974 (PL 93-378). Substantial research and development is needed to quantify constraints and outputs in a land use planning context. The effectiveness of fuels management as a control strategy for wildfires has not been assessed. An attempt should be made to offset smoke from forest burning against reductions in wildfire smoke in managing the air resource. Also, Federal land managers have a new responsibility to cooperate with Federal and State agencies in drafting ambient air quality standards and implementation plans that will protect wildland values. Primary concerns are the need for visibility standards in wilderness and the protection of vegetation and wildlife from the harmful effects of air pollution. Currently, knowledge of air quality effects on resource values is incomplete.

Clean air is a resource having measurable outputs and to which constraints and objective functions can be applied. The air quality degradation over a forest is largely predetermined during fire management planning and the setting of fuel management standards. National Forest land managemet plans, in turn, define the alternatives for fire management and determine the levels of activity required in fuels management. Air quality control regulations and the applicable smoke management plan represent constraints on fuel treatment which, in turn, may constrain fire suppression policy, timber harvesting options, and range management alternatives. Creating recreation opportunities will add to the complexity of the plans by creating new visibility requirements, however, these recreation opportunities will alter the creation of activity fuels and the risk of major

wildfires. A complex set of decision models, analytical tools, and the data management techniques are required to resolve the internal and external conflicts resulting from these interactions.

The land use planning process, with linear or goal programming as tools to resolve conflicts (Alston 1972, Buckman and Fight 1975, Bell 1976), is the obvious framework in which to include air quality considerations in decisionmaking. The production of clean air is conceptually similar to the production of clean water from a managed forest. In fact, the two are explicitly linked in the Forest Service's Renewable Resource Assessment required by PL 95-378. The air quality goals associated with the eight Alternative Program Directions finally considered were: (USDA Forest Service 1976)

Goal A: Meet minimum air and water quality standards.

Goal B: Meet minimum air and water quality standards. *Selectively improve,* commensurate with benefits produced, air quality, water quality and supply... .

Goal C: Meet minimum air and water quality standards. *Emphasize improvement* of soil productivity, air and water quality, and water supply, meet or exceed other land stewardship standards.

The "accelerated investment" alternative, which is the Recommended Renewable Resource Program stipulated "Goal C," is:

> Research would be strengthened to improve knowledge about air, soil, and water resources, as well as solutions to specific problems that obstruct the effective management of these resources on both Federal and non-Federal lands. Important areas of research would include the nature and extent of nonpoint sources generated by resource management... .

Obstacles to incorporating air quality goals and constraints into a quantitative land use planning scheme are embodied in our inability to model fire protection, fuel management, and land use effects on the atmosphere. The economic impact of alternatives is the common denominator for evaluating tradeoffs in land use planning and is a required input to air quality regulations. Decisions limiting use of prescribed fire would obviously have great impact on forest economics. Economic analyses of burning, alternate treatments, and no-treatment options are essential for management planning and for feedback to agencies responsible for setting control strategies. Economic models for these purposes are not currently available.

RESEARCH PRIORITIES

At the National Fire Effects Workshop in April 1978, the Air Quality Work Group reached the consensus that there was a need for an analysis of research needs. Justification for the suggested research is included in the sections on research review and research applications of this report. Independent expressions of need, by other authors, are found in the section on prior reviews.

The work group identified five research areas as incumbent on the problem stated in the first section. No attempt was made to set priorities in the general research areas, as additional knowledge from all areas must be combined to satisfy each user's need. The research areas would:

1. Provide quantitative smoke management systems.
2. Characterize the chemistry and physics of emissions.
3. Model atmospheric transport, diffussion, transformation, and removal mechanisms.
4. Identify receptor responses to wildland smoke.
5. Investigate tradeoffs made in substituting alternative methods for prescribed fire.

Priorities were established for tasks within each general research area, based on consideration of their:

1. Degree of need (including timeframe).
2. Sensitivity to research input.
3. Probability of success.
4. Economy of effort.

Systems development needs were also assigned priority in our discussions. Such needs were identified where modeling, inventory, reporting, or information processing is required to serve the identified user group. A discussion of research priorities follows.

Quantitative Smoke Management Systems

Smoke Management Planning Process—Priority 1

Develop systems necessary to support smoke management decisions. This task would provide mechanisms for making impact analyses and source assessments based on the expanding knowledge from research.

Source Strength Estimators—Priority 2

Provide a smoke management reporting system for emission rates based on our ability to inventory and predict fuel consumption, fire behavior, heat release rates, and source control measures.

Meteorological Requirements—Priority 2

Provide the data network and modeling scheme necessary to calculate a "dilution factor," i.e., the change in pollutant concentrations and character between a source and potential receptors.

Plume Rise Adjustments—Priority 3

Continue adapting plume rise models necessary to predict the vertical distribution of emissions in smoke from wildland fires.

Smoke Chemistry and Physics

Emission Rate Model—Priority 1

Continue research that relates emissions and heat release rates to fuelbed characteristics and fire behavior.

Smoke Character—Priority 2

Advance our knowledge of the constituents of particulate matter and organic vapors in smoke. Identify hazardous and reactive compounds, relating their genesis to fuel and combustion character.

Measurement Methods—Priority 3

Develop field methods to monitor emission rates and smoke chemistry from operational fires.

Secondary Emissions—Priority 4

Investigate the potential for secondary reactions of emissions downstream from their source. Consider the effects of interactions with other atmospheric contaminants, irradiation, etc.

Atmospheric Transport and Removal

Meteorological Models for Complex Terrain—Priority 1

Continue development of winds and dispersion models for boundary layer flow and mesoscale transport of smoke over mountainous terrain. Test models and derive suitable coefficients.

Deposition Processes—Priority 2

Investigate the mechanisms of removal mechanisms for wildland smoke. Examine canopy interactions, fallout, and local deposition.

Atmospheric Chemistry—Priority 3

Interact with broader scientific community to establish the effect of reactive pollutants on the biosphere. No new research should be centered in forestry research organizations, but expertise is required to interpret and apply research results.

Climatic Effects—Priority 4

Provide expertise to evaluate the potential contribution of wildland fires to climatic changes. Interaction, rather than new research, is required.

Receptor Response

Visibility Requirement—Priority 1

Identify and quantify the visibility needs of wildland users. Recommend standards for particulate and sulfate pollution from all sources impacting Class I visibility areas.

Human Health Effects—Priority 1

Provide expertise (not research) to evaluate the potential impact of wildland smoke on community health problems.

Effects on Forest Organisms—Priority 2

Continue to investigate the role of wildland vegetative communities as a sink for atmospheric contaminants; and quantify adverse effects of anthropogenic pollution sources on wildland organisms.

Inherent Tradeoffs

Land Use Planning Needs—Priority 1

Develop the necessary simulation models to evaluate interactions of and use policy with air resource management. Describe pollution potential and air quality requirements of land use alternatives and commodity production alternatives. Incorporate air resource management and fuels management needs into the land use planning process.

Wildfire Emissions Tradeoff—Priority 2

Evaluate the incremental increase in wildfire occurrence and potential air quality impact from wildfires resulting from decreases in prescribed burning activity.

Wildfire Economics Tradeoff—Priority 3

Describe the potential resource loss and economic costs associated with wildfire damages resulting from decreased prescribed burning activity.

Site Productivity Tradeoffs—Priority 4

Investigate the results of reduced prescribed fire activity on nutrient cycling, successional response, ecosystem stability, regeneration success, and other site productivity factors.

SUMMARY AND CONCLUSIONS

Air resource management is an essential part of wildland management. Clean air is necessary for wilderness users and for the continued productivity of forest and rangelands. Recent legislation requires Federal land managers to cooperate with State and other Federal agencies in defining and regulating rural air quality needs. This report summarizes both the legal requirement and the state-of-knowledge for understanding the effects of air pollution on wildland values. Publications are few in number, but significant in their implication that the role and response of forest lands is greater than heretofore believed. The authors conclude that insufficient knowledge exists to quantify natural background levels of atmospheric contaminants or to evaluate the economic and ecologic results of alternative air resource management strategies.

Land managers are also required by law and policy to limit the emission of air pollutants from prescribed fire and to minimize their impact on society. Prescribed fires are an important source of air pollution where particulates (visibility) and, possibly, carbon monoxide and hydrocarbons are a concern. In general, managers must have the ability to predict how much smoke will be created, and where it will go in order to discharge their responsibility. This report summarizes our current understanding of the processes and the magnitude of prescribed fire as a source of emissions and of community air pollution.

A wealth of knowledge has been gained in the last decade. Research has described, in some detail, the contents of forest fire smoke. Emission yields are found to vary over two orders of magnitude depending on fuel type (especially the presence of needles and live fuels) and fire behavior (especially fire intensity and whether a backing or heading fire was used). Particulate emissions are found to have the greatest potential for causing air pollution because of their amount (ranging from 6 to 200 pounds and averaging near 50 pounds per ton of fuel burned), their effect on visibility (owing to a preponderance of submicrometer particles), and their high organic content (including their role as adsorption surfaces).

Emissions source strength has been shown to be somewhat subject to control measures such as backfiring, mopping up, yarding unmerchantable residues, and scheduling in order to minimize the highly polluting smoldering combustion phases. However, our knowledge is incomplete in that we still cannot create a predictive model incorporating the influence of fuel condition and fire behavior on source strength; nor do we possess adequate emission factors for many fuel types. Equally important is our incomplete understanding of those fractions

of forest fire smoke that may affect human health.

Dispersion modeling, using a Gaussian plume model approach, has been found to be useful for predicting downwind pollutant concentrations from fires for short distances over level terrain. Basic approaches for modeling dispersion over complex terrain have been advanced, but much uncertainty remains in the numerical coefficients to be used in the calculations and in the data inputs that will be required. Smoke management and the efficiency of air resource allocation systems will take a quantum step when such models are available and systematized, but several years of development are still needed.

The contribution of wildland burning to air pollution is, in a large part, predetermined in the land use planning process. Goals for timber and forage production, as well as standards for fire and fuels management, are set with little regard for air resource management needs. Planning models to interface fire management, commodity production, and land use with air quality are sorely in need.

Information gained through research will be essential in the next several years as new air quality legislation is interpreted and applied; as quantitative smoke management and source assessment systems are developed; and as land use decisions are made. Appropriate use of the research summarized herein is necessary to provide the greatest good from wildland management. Much remains to be done.

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